National Defence
Research and Development Branch

Défense nationale
Bureau de recherche et développement

TECHNICAL MEMORANDUM 98/215
June 1998

PREDICTION OF EXTREME AND FATIGUE SEA LOADS USING LINEAR THEORY

Kevin A. McTaggart

19981106 119

Defence Research Establishment Atlantic

Centre de Recherches pour la Défense Atlantique

DEFENSIO PER SCIENTIAM

Canada

DEFENCE RESEARCH ESTABLISHMENT ATLANTIC

9 GROVE STREET

P.O. BOX 1012
DARTMOUTH, N.S.
CANADA B2Y 3Z7

TELEPHONE: (902) 426-3100
FACSIMILE: (902) 426-9654

CENTRE DE RECHERCHES POUR LA DÉFENSE ATLANTIQUE

9 GROVE STREET

C.P. BOX 1012
DARTMOUTH, N.É.
CANADA B2Y 3Z7

National Defence
Research and Development Branch

Défense nationale
Bureau de recherche et développement

PREDICTION OF EXTREME AND FATIGUE SEA LOADS USING LINEAR THEORY

Kevin A. McTaggart

June 1998

Approved by: R.W. Graham
Head / Warship Signatures and Safety

TECHNICAL MEMORANDUM 98/215

Defence Research Establishment Atlantic

Centre de Recherches pour la Défense Atlantique

Canada

Abstract

This report presents three different approaches for determining exceedence probabilities of ship sea loads using linear strip theory. The first two approaches use nominal maximum loads for hourly and variable duration seaways, while a third approach considers individual load cycle amplitudes in all seaways. Of the three approaches, the load cycle approach appears to be most useful and can be used for both fatigue and ultimate load computations. Sample computations for the Canadian Patrol Frigate demonstrate the application of the methods. Gumbel distributions provide good fits to computed lifetime load exceedence probabilities. For load cycle and nominal hourly maximum loads, Weibull distributions provide superior fits. Future work should include three-dimensional hydrodynamic forces, nonlinear load effects, and the influence of wave conditions on ship speed and heading.

Résumé

Le présent rapport fait état de trois approches différentes utilisées pour déterminer, à l'aide d'une théorie de dépouillement linéaire, l'indice de dépassement des charges exercées par la mer sur un navire. Les deux premières approches reposent sur le calcul des charges maximales nominales pour état de mer de durée variable et de durée d'une heure, alors que la troisième approche se fonde sur l'amplitude de cycles de charge individuels dans des mers de tous les états. Parmi les trois approches, celle des cycles de charge semble être la plus utile et peut servir tant aux calculs de fatigue qu'aux calculs de la charge de rupture. Des échantillons de tels calculs effectués sur une frégate canadienne de patrouille démontrent l'application de cette méthode. Les distributions de Gumbel donnent une bonne équivalence des probabilités de dépassement des charges de durée calculée. En ce qui concerne le cycle de charge et les charges maximales horaires nominales, les distributions Weibull donnent des équivalences supérieures. Les prochains travaux devraient examiner les forces hydrodynamiques en trois dimensions, les effets de charges non linéaires et l'influence de l'état des vagues sur la vitesse et la direction du navire.

DREA TM/98/215

PREDICTION OF EXTREME AND FATIGUE SEA LOADS USING LINEAR THEORY

by

Kevin A. McTaggart

EXECUTIVE SUMMARY

Introduction

The rational design of ship structures requires application of probabilistic methods. This technical memorandum presents three different methods for computing exceedence probabilities for fatigue and lifetime maximum sea loads. The first approach determines a nominal maximum sea load for each hourly seaway that the ship encounters. The second approach computes the nominal maximum load for each seaway based on its expected encounter duration during the ship life. The third approach considers the variation of individual load cycle amplitudes for all conditions. Sample computations for the Canadian Patrol Frigate (CPF) demonstrate the application of the three methods.

Principal Results

The nominal hourly, nominal seaway, and load cycle approaches all give useful results; however, the load cycle approach appears to be the most rigorous and useful. Output from the load cycle approach includes conditional distributions for ship and wave conditions when sea loads exceed a specified threshold value. Gumbel distributions provide good fits to computed lifetime load exceedence probabilities. For load cycle and nominal hourly maximum loads, Weibull distributions provide superior fits. For extreme lifetime loads acting on the CPF, the midships vertical bending moment is approximately three times greater than the midships horizontal bending moment.

Significance of Results

It is recommended that the load cycle approach be used to determine sea load exceedence probabilities for both fatigue and lifetime extreme computations. Conditional probabilities of ship and sea conditions given high sea loads can be used to determine which conditions warrant more detailed analysis. The current sample computations for the CPF indicate that maximum lifetime loads are likely to be caused by significant wave heights of approximately 15 m, suggesting that nonlinear effects will be very important.

Future Plans

The current load cycle approach will likely be enhanced in several ways. A program will be developed to determine composite wave scattergrams based on areas and seasons of ship operations. Future developments should consider the dependence of ship operations on wave

conditions. For example, a ship will usually reduce speed in severe head seas to reduce the incidence of slamming. Although the current implementation is based on strip theory, it should be extended to include three-dimensional hydrodynamic effects, which are important for the CPF. Nonlinear effects will be important for severe sea conditions. DREA is currently sponsoring development of time domain methods which include nonlinear forces. Attention should also be given to accurate statistical modelling of extreme seas which influence ultimate strength design.

Contents

Notation

D	duration
$F_X(X)$	cumulative distribution function of variable X
$f_X(X)$	probability density function of variable X
f_Z	zero-crossing frequency
$\overline{f}_Z$	mean zero-crossing frequency
H_s	significant wave height
$H_{s,lower}$	lower bound of significant wave height range
$H^i_{s,lower}$	$H_{s,lower}$ value for load event with rank i
$H_{s,mid}$	middle value of significant wave height range
k_X	Weibull distribution parameter
N_{cycle}	number of load cycles
N_{hour}	number of hours of ship operation
N_{seaway}	number of seaways encountered during ship life
N_X	number of discretized values of variable X
$p(X_i)$	probability of occurrence for discrete value X_i
$Q_X(X)$	exceedence probability of variable X
$Q_{X\|Y}(X\|Y)$	conditional exceedence probability of variable X given Y
T_p	peak wave period
T^i_p	T_p value for load event with rank i
T_z	zero-crossing period
u_X	Gumbel distribution parameter for variable X
V_s	ship speed
V^i_s	ship speed for load event with rank i
V_{s-i}	discretized value of V_s
X	random variable
X_{cycle}	load cycle amplitude
X^*_{cycle}	minimum threshold for load cycle amplitude
$X_{D,\alpha}$	nominal maximum with exceedence probability α over duration D
$X^i_{D,\alpha}$	$X_{D,\alpha}$ value for load event with rank i
X_i	discretized value of random variable X
$X_{seaway,\alpha}$	nominal maximum with exceedence probability α in a seaway
α	exceedence probability for nominal hourly maximum load
α_X	Gumbel distribution parameter for variable X
β	incident sea direction (relative to ship speed)
β^i	β value for load event with rank i
β_j	discretized value of β
β_X	Weibull distribution parameter for variable X
γ	Euler's constant (≈ 0.5772)
δ	lifetime exceedence probability
μ_X	mean value of variable X
σ	standard deviation (RMS value) of random process
σ_X	standard deviation of variable X

1 Introduction

A major trend in current ship structural design and maintenance is the evolution toward probabilistic approaches. Mansour et al. [1] give an overview of the application of reliability methods to ship structures. Within DND, the Improved Ship Structural Maintenance Management (ISSMM) project is developing probabilistic approaches for naval ships.

The hydrodynamic loads on ship structures are highly variable; thus, any probabilistic approach to ship structures must include a probabilistic treatment of the hydrodynamic loads. A rational probabilistic approach can determine the statistical distribution of sea loads, which can then be used as input for a structural reliability model. Several authors present approaches for determining statistical distributions of sea loads. Sikora et al. [2] present a semi-empirical approach for estimating vertical bending moments including nonlinear and whipping effects. Guedes Soares and Schellin [3] give a rational method for including nonlinear effects when deriving long-term distributions for vertical bending moment. Jensen and Dogliani [4] use a similar approach based on quadratic strip theory for predicting bending moment distributions. They indicate that nonlinear effects can be significant for ships that are not wall-sided.

The current report describes initial efforts within DND to derive statistical distributions of sea loads acting on a naval frigate. The computer program SHIPMO7 [5] provides linear predictions of sea loads. SHIPMO7 provides generally good predictions of sea loads [6, 7], with some overprediction (typically 20-30 percent) of vertical bending moment for a transom stern frigate such as the Canadian Patrol Frigate (CPF). The linear sea load predictions of SHIPMO7 are coupled with wave statistics from British Maritime Technology (BMT) [8]. Three different methods are presented for determining load exceedence probabilities during the life of a ship. The first method is based on the nominal maximum loads in all of the one hour seaways encountered by the ship. The second method is based on the nominal maximum loads using the expected duration of each seaway during the lifetime of the ship. The third method considers all of the individual wave load cycles encountered by the ship.

The following section presents the theory for the nominal hourly load approach, which is followed by the nominal seaway load approach. Section 4 gives the alternative approach based on individual load cycles. The fitting of Weibull and Gumbel distributions to derived data is presented in Section 5. The numerical implementation of the theory is given in Section 6. Section 7 gives an example of application of the methods to the CPF. Recommendations for future work to include nonlinear effects and mission profiles are given in Section 8, which is followed by final conclusions.

2 Nominal Hourly Load Approach

In the first approach for computing sea load probabilities, a nominal hourly maximum load will be taken for each combination of ship speed, heading, significant wave height, and peak wave period. Assumptions of linearity and narrow bandedness permit load amplitude in a random seaway to be modelled using a Rayleigh distribution as follows:

$$f_{X_{cycle}}(X_{cycle}) = \frac{X_{cycle}}{\sigma^2} \exp\left[\frac{-X_{cycle}^2}{2\sigma^2}\right] \qquad (2.1)$$

where $f_{X_{cycle}}(X_{cycle})$ is the probability density function for load amplitude X_{cycle} in a single load cycle and σ is RMS load in a seaway. The nominal maximum load $X_{D,\alpha}$ with probability of exceedence α during duration D is given by:

$$X_{D,\alpha} = \sigma \sqrt{2 \ln \left(\frac{D}{\alpha T_z} \right)} \tag{2.2}$$

where T_z is the zero-crossing period of the load process. For the present analysis, the duration D is taken as being one hour because a loading process can generally be considered stationary (i.e. the standard deviation σ and zero crossing period T_z will not change significantly) during a one hour period. Table 1 shows the ratio of maximum to RMS load for nominal seaway conditions. For the example given, the nominal maximum load increases by approximately ten percent as the exceedence probability is decreased by a factor of ten. For structural design, an exceedence probability of the order of 0.01 would likely be acceptable for computing the nominal maximum load in a one hour seaway.

Table 1: Ratio of Maximum to RMS Load for One Hour Duration and Zero-Crossing Period of 10 Seconds

Exceedence probability α	$X_{hour,\alpha}/\sigma$
0.1	4.05
0.01	4.58
0.001	5.06
0.0001	5.49

The concept of the nominal hourly load in a seaway simplifies the computation of long term load exceedence probabilities. The current analysis assumes that ship speed and heading are independent variables but considers the joint distribution of significant wave height and peak wave period, which can be obtained from wave climate databases such as BMT Global Wave Statistics. The procedure for computing long term load exceedence probabilities is as follows:

1. compute reference RMS ship loads and zero-crossing periods in irregular seaways for all relevant combinations of ship speed V_s, heading β, and peak wave period T_p (only one significant wave height is required per peak wave period),

2. provide input probabilities for ship speed and heading, and a wave statistics file with joint distribution of wave height and peak wave period,

3. compute nominal hourly wave loads for all existing combinations of ship speed, heading, peak wave period, and significant wave height,

4. rank nominal maximum wave loads from highest to lowest,

5. compute long term exceedence probabilities for nominal maximum wave loads.

When performing step 3 above, the nominal hourly load $X_{hour,\alpha}(V_s, \beta, H_{s,lower}, T_p)$ is computed at the lower wave height $H_{s,lower}$ for each wave height range in the wave scattergram. The exceedence probability $Q_{X_{hour,\alpha}}$ for each of the ranked loads is then computed as follows:

$$\begin{aligned} Q_{X_{hour,\alpha}}\left(X^i_{hour,\alpha}(V^i_s, \beta^i, H^i_{s,lower}, T^i_p)\right) &= \\ Q_{X_{hour,\alpha}}\left(X^{i-1}(\alpha, V^{i-1}_s, \beta, H^{i-1}_{s,lower}, T^{i-1}_p)\right) &+ p(V^i_s)\, p(\beta^i)\, p(H^i_{s,lower}, T^i_p) \end{aligned} \tag{2.3}$$

where the superscript i on each variable denotes the value of the variable associated with the load event having rank i, with $i = 1$ denoting the highest long term load. A typical computation procedure will have approximately 7 ship headings, 15 significant wave heights, and 11 peak wave periods, although many of the combinations of wave height and period can be neglected because they will not occur.

When considering representative wave periods in irregular seas, it should be noted that SHIPMO7 uses peak wave period T_p, while BMT Global Wave Statistics uses zero-crossing wave period T_z. The following conversion can be used:

$$T_p = 1.408\, T_z \tag{2.4}$$

A key benefit of the nominal hourly load approach is that it applies rankings to discrete combinations of ship speed, heading, significant wave height, and peak wave period; thus, the approach indicates which conditions produce the highest loads. This information can form the basis for more sophisticated treatment of nonlinear effects and possible correlation between variables such as significant wave height and ship speed.

The current procedure estimates exceedence probabilities for maximum hourly loads. The following equation can be used to predict the probability distribution of the nominal maximum load during ship life:

$$F_{X_{life}}(X_{life}) = \left[F_{X_{hour,\alpha}}(X_{hour,\alpha})\right]^{N_{hour}} \tag{2.5}$$

where $F_{X_{life}}(X_{life})$ is the cumulative distribution function of the lifetime maximum load X_{life} and N_{hour} is the number of hours of operation during the ship life. For a ship spending 30 percent of its 30 year life at sea, the number of hours at sea will be approximately 80,000.

3 Nominal Seaway Load Approach

Equation (2.2) given above indicates that the maximum load with exceedence probability α in a seaway is dependent upon seaway duration D. When considering lifetime maximum loads, the above approach does not consider that different seaways will have different expected durations, and this may affect the maximum loads. To circumvent this problem, nominal maximum loads can be considered on the basis of seaway rather than on the basis of hour.

For the present discussion, a seaway is considered to be a combination of ship speed, ship heading, significant wave height, and peak wave period. The number of different seaways encountered by the ship is given by:

$$N_{seaway} = N_{V_s} \times N_\beta \times \text{Number of cells with } p(H_{s,lower}, T_p) > 0 \tag{3.1}$$

The average duration for each seaway is given by:

$$D(V_s, \beta, H_s, T_p) \quad = \quad L\, p(\text{at sea})\, p(V_s)\, p(\beta)\, p(H_s, T_p) \tag{3.2}$$

where L is the ship life and $p(\text{at sea})$ is the fraction of the ship life spent at sea. The nominal maximum load for each seaway, $X_{seaway,\alpha}$, is calculated using Equation (2.2) using the seaway duration from Equation (3.2). The exceedence probabilities for nominal seaway maximum loads are evaluated using the same procedure as for nominal hourly maximum loads. The following equation gives the cumulative distribution for lifetime maximum load based on the nominal seaway maximum loads:

$$F_{X_{life}}(X_{life}) \quad = \quad \left[F_{X_{seaway,\alpha}}(X_{seaway,\alpha})\right]^{N_{seaway}} \tag{3.3}$$

4 Load Cycle Approach

The nominal hourly and seaway load approaches developed above have two main shortcomings. The use of a nominal maximum load does not rigorously consider the statistical variation of maximum load during each hour or seaway. The second shortcoming is that the nominal load approaches do not provide the statistical distribution of individual load cycle amplitudes, which is typically used for fatigue computations.

Exceedence probabilities for load cycle amplitudes can be computed using the procedure described by Paulling [9]. Again assuming a Rayleigh distribution for load cycle amplitude in a given seaway, the long term exceedence probability for load cycle amplitude in all seaways is:

$$Q_{X_{cycle}}(X_{cycle}) = \\ \sum_{i=1}^{N_{V_s}} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{H_s}} \sum_{l=1}^{N_{T_p}} p(V_{s-i})\, p(\beta_j)\, p(H_{s,mid-k}, T_{p-l})\, \frac{f_Z}{\overline{f}_Z}\, \exp\left(\frac{-X_{cycle}^2}{2\,\sigma^2}\right) \tag{4.1}$$

where X_{cycle} is load amplitude in a single loading cycle, $H_{s,mid-k}$ is the middle value of significant wave height for range k, f_Z is zero-crossing frequency in a seaway, and $\overline{f}_Z$ is average long-term zero-crossing loading frequency given by:

$$\overline{f}_Z \quad = \quad \sum_{i=1}^{N_{V_s}} \sum_{j=1}^{N_\beta} \sum_{k=1}^{N_{H_s}} \sum_{l=1}^{N_{T_p}} p(V_{s-i})\, p(\beta_j)\, p(H_{s,mid-k}, T_{p-l})\, f_Z \tag{4.2}$$

The probability distribution of maximum lifetime load can then be computed as follows:

$$F_{X_{life}}(X_{life}) \quad = \quad \left[F_{X_{cycle}}(X_{cycle})\right]^{N_{cycle}} \tag{4.3}$$

where N_{cycle} is the number of load cycles in the ship life, which is given by:

$$N_{cycle} \quad = \frac{3600\, N_{hour}}{\overline{f}_Z} \tag{4.4}$$

A naval frigate will experience of the order of 10^7 wave loading cycles during its life.

When designing for extreme loads, it is useful to know which conditions cause those extreme loads. For loads exceeding a threshold level X_{cycle}^*, the theorem of Bayes can be applied to

determine conditional probability distributions for ship speed, heading, and wave conditions. For example, the following equation gives the conditional probability distribution of ship speed for load amplitudes exceeding X^*_{cycle}:

$$p(V_{s-i}|X_{cycle} > X^*_{cycle}) = \frac{p(V_{s-i})\, Q_{X_{cycle}|V_s}(X^*_{cycle}|V_{s-i})}{Q_{X_{cycle}}(X^*_{cycle})} \tag{4.5}$$

Similar equations can be applied to determine conditional distributions for ship heading, wave height, and wave period.

5 Fitting of Gumbel and Weibull Distribution Parameters

Once load probabilities are computed using any of the three approaches described above, it is useful to determine fitted statistical distributions for load probabilities. A fitted statistical distribution allows load probabilities to be described by a small number of parameters. A fitted distribution also facilitates interpolation or extrapolation of load probabilities.

Thoft-Christensen and Baker [10] give a useful overview of statistical distributions used in engineering reliability. For sea loads acting on a ship, the Gumbel and Weibull distributions are commonly used. The cumulative distribution function of the Gumbel distribution is as follows:

$$F_X(X) = \exp\{-\exp[\alpha_X(X - u_X)]\} \tag{5.1}$$

where u_X and α_X are distribution parameters. The mean μ_X and standard deviation σ_X of the Gumbel distribution are related to the distribution parameters as follows:

$$\mu_X = u_X + \frac{\gamma}{\alpha_X} \tag{5.2}$$

$$\sigma_X = \frac{\pi}{\alpha_X\sqrt{6}} \tag{5.3}$$

where γ is Euler's constant (≈ 0.5772).

The Weibull distribution can be described by 2 or 3 parameters, where the third parameter represents a lower threshold (typically non-zero) for the variable X. The present study considers the 2-parameter distribution, for which exceedence probability is given by:

$$Q_X(X) = \exp\left[-\left(\frac{X}{k_X}\right)^{\beta_X}\right] \tag{5.4}$$

where k_X and β_X are distribution parameters. The mean and standard deviation for the 2-parameter Weibull distribution are:

$$\mu_X = k_X\,\Gamma\left(1 + \frac{1}{\beta_X}\right) \tag{5.5}$$

$$\sigma_X = k_X\left[\Gamma\left(1 + \frac{2}{\beta_X}\right) - \Gamma^2\left(1 + \frac{1}{\beta_X}\right)\right] \tag{5.6}$$

where $\Gamma(y)$ denotes the Gamma function with argument y.

Two methods are available for determining fitted Gumbel and Weibull distribution parameters for sea loads. The method of moments relates the distribution parameters to the computed mean and standard deviation for the variable X. The second method uses a least squares linear fit between the variable X or its transformation (e.g. $\ln X$) and exceedence probability $Q_X(X)$ or its transformation (e.g. $\ln Q_X(X)$). A significant advantage of the least squares method is that it can be applied to a limited probability range of greatest interest for design, such as the upper range of sea loads or the lower range of ship strength. Applying a least squares fit to a limited range of interest generally produces a better statistical fit within that range.

The equation for determining a least squares fit of Gumbel parameters is as follows:

$$X = \frac{1}{\alpha_X} \ln[-\ln(F_X(X))] + u_X \tag{5.7}$$

Placing the variable X on the left-hand side of the above equation minimizes the error in X for a given value of $\ln[-\ln(F_X(X))]$. The regression fit has a slope of $1/\alpha_X$ and an intercept of u_X. For the Weibull distribution, the parameters can be determined through a least-squares fit of the following:

$$\ln X = \frac{\ln[-\ln(Q_X(X))]}{\beta_X} + \ln k_X \tag{5.8}$$

The resulting regression fit has a slope of $1/\beta_X$ and an intercept of $\ln k_X$. When evaluating Equations (5.7) and (5.8), the terms $\ln[-\ln(F_X(X))]$ and $\ln[-\ln(Q_X(X))]$ become undefined when the exceedence probability $Q_X(X)$ approaches either zero or one; therefore, a Gumbel or Weibull least squares fit cannot include points with exceedence probabilities of zero or one. Furthermore, the term $\ln X$ in Equation (5.8) becomes undefined when X approaches zero. When evaluating lateral sea loads, the occurrence of zero values in head and following long crested seas necessitates care when applying Gumbel and Weibull fits.

6 Numerical Implementation

The computer program EXTRMLIN implements the nominal hourly load, nominal seaway load, and load cycle approaches described above. Appendix A.1 gives the input format.

Numerical implementation was relatively straightforward. The most critical numerical aspect is the accurate computation of probabilities. All probabilities are stored using double precision, which is required because exceedence probabilities of interest range between 10^{-10} and 1.0. The input wave scattergram is normalized to correct any roundoff errors. When computing probabilities for sea loads, values associated with small exceedence probabilities are of greatest interest. To minimize roundoff errors for exceedence probabilities, most probability computations are done using exceedence probability $Q_X(X)$ rather than the cumulative distribution function $F_X(X)$. The relationship between the exceedence probability and cumulative distribution function is:

$$Q_X(X) = 1 - F_X(X) \tag{6.1}$$

Equations 2.3 and 4.1 give examples of formulations where exceedence probability is used to maintain accuracy.

When determining lifetime maxima from large numbers of events using Equations 2.5 and 4.3, numerical precision becomes a problem for small exceedence probabilities because of inaccuracies in $F_X(X)$ as it approaches unity. When determining the cumulative distribution function $F_{X_{max,n}}(X_{max,n})$ of the maximum of n samples of variable X, the following equation can help to preserve numerical accuracy:

$$\ln F_{X_{max,n}}(X_{max,n}) = n \ln F_X(X) \tag{6.2}$$

For small values of $Q_{X_{max,n}}(X_{max,n})$, the following Taylor series expansion can be used to maintain numerical accuracy when evaluating exceedence probability from $\ln F_{X_{max,n}}(X_{max,n})$:

$$\begin{aligned} Q_{X_{max,n}}(X_{max,n}) &\approx -\ln F_{X_{max,n}}(X_{max,n}) - \frac{\left[\ln F_{X_{max,n}}(X_{max,n})\right]^2}{2} \\ &\quad - \frac{\left[\ln F_{X_{max,n}}(X_{max,n})\right]^3}{6} - \frac{\left[\ln F_{X_{max,n}}(X_{max,n})\right]^4}{24} \end{aligned} \tag{6.3}$$

For $Q_{X_{max,n}}(X_{max,n}) < 0.01$, Equation (6.3) gives a relative error of less than one millionth of the exceedence probability (e.g. less than 10^{-8} for $Q_{X_{max,n}}(X_{max,n}) = 0.01$). The following Taylor series expansion can simplify the evaluation of $\ln F_{X_{max,n}}(X_{max,n})$:

$$\begin{aligned} &\ln F_{X_{max,n}}(X_{max,n}) \approx \\ &\quad n\left[-\frac{Q_X(X)}{F_X(X)} + \frac{1}{2}\left(\frac{Q_X(X)}{F_X(X)}\right)^2 - \frac{1}{3}\left(\frac{Q_X(X)}{F_X(X)}\right)^3 - \frac{1}{4}\left(\frac{Q_X(X)}{F_X(X)}\right)^4\right] \end{aligned} \tag{6.4}$$

The above series will give a relative error in $\ln F_{X_{max,n}}(X_{max,n})$ of less than a millionth when $Q_X(X)$ is less than 0.01.

7 Example Calculations for Canadian Patrol Frigate

Sample calculations have been performed for the Canadian Patrol Frigate based on the sample case of the SHIPMO7 manual [5]. Appendix A.2 gives sample input for the program EXTRMLIN and Appendix B.2 gives sample output. This section presents exceedence probabilities for vertical and horizontal bending moments at midships.

For the sample case, the ship has a 30 year life and spends 30 percent of its time at sea. All time at sea is spent in sea area 15 [8], which extends from Nova Scotia and Newfoundland to approximately halfway across the Atlantic. This area has a relatively severe wave climate; thus, the resulting sea loads are likely conservative. The ship divides its time evenly between travelling at 10 and 18 knots. Waves are assumed to be long crested and modelled by a Bretschneider spectrum, with a uniform distribution of relative sea directions.

For fitting of Weibull and Gumbel distributions, the input range of exceedence probabilities is $0.0 < Q_X(X) < 0.9$. Trial computations with the full range of exceedence probabilities $0.0 < Q_X(X) < 1.0$ gave inferior matching between computed and fitted distributions. Initial fitting of distribution parameters to computed exceedence probabilities for vertical bending moment was relatively simple. Additional fitting of parameters for horizontal bending moment presented new challenges. When fitting distribution parameters to nominal hourly values, the fitted distributions initially provided poor matches to computed exceedence probabilities. These

poor matches occurred because SHIPMO7 gives non-zero (but very small) lateral loads in head seas, which arise from a non-zero value when evaluating the cosine of 180 degrees. To avoid the resulting problems when fitting distributions to ranked nominal hourly maximum loads, the fitting procedures exclude nominal hourly maximum loads which are less than 0.001 times the highest nominal hourly maximum.

7.1 Vertical Bending Moment at Midships

Figures 1 to 6 show vertical bending moment at midships versus exceedence probability. For the nominal hourly sea loads, an hourly exceedence probability of $\alpha = 0.10$ was used for the sample case as it was found to produce similar maximum lifetime loads for the nominal hourly and load cycle approaches. The nominal seaway approach produces significantly smaller lifetime loads than the other two approaches. These smaller lifetime loads are due to the smaller average exposure times for the extreme sea conditions, which were found to be significantly less than one hour. In reality, an extreme sea condition will either occur for at least an hour or will not occur during the ship lifetime; thus, the average exposure times used for nominal seaway maxima produce misleading results. Due to the relatively poor results of the nominal seaway approach, it is omitted from most of the following discussion.

In Figure 2, the plotted lines for lifetime vertical bending moment from the nominal hourly and nominal seaway approaches have noticeable discontinuities because the probabilities are computed from small numbers of discrete conditions. The fitted distributions to nominal hourly and load cycle vertical bending moments in Figures 3 and 4 indicate that both the Gumbel and Weibull distributions provide good fits to the computed data; however, the Gumbel distributions have the disadvantage of incorrectly giving negative bending moments for load cycles as exceedence probability approaches 1.0. Consequently, the Weibull distribution is recommended for modelling nominal hourly maximum or load cycle amplitude. For lifetime extreme bending moment, Figures 5 and 6 indicate that the Gumbel distribution provides a significantly better fit than the Weibull distribution. The superior fit of the Gumbel distribution is expected for lifetime maxima because it is based on the asymptotic behaviour of largest extreme values.

Table 2 gives means and standard deviations for fitted distributions of vertical bending moment at midships. The nominal hourly and load cycle amplitude values are based on Weibull distributions, while the lifetime maxima are based on Gumbel distributions. It should be emphasized that the properties of the lifetime maximum based on nominal hourly maxima will depend on the hourly exceedence probability α used to determine the nominal maximum. For the present case of $\alpha = 0.1$, the lifetime maxima are similar for the two different approaches. The lifetime maximum design vertical bending moment depends on the probability of exceedence δ for the lifetime maximum. For $\delta = 0.01$, the design vertical bending moment would be approximately 780 MN·m.

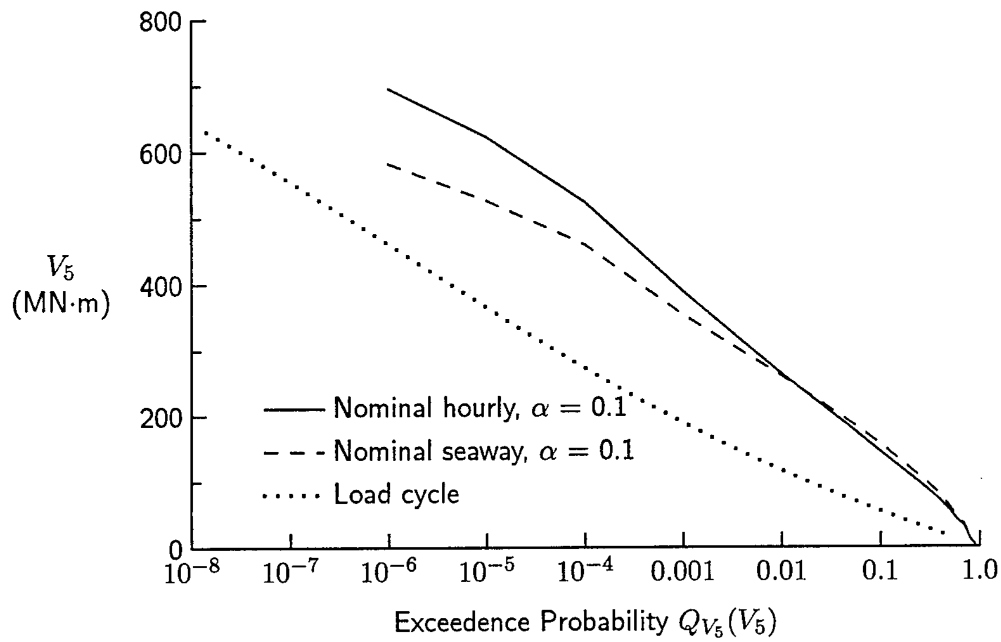

Figure 1: Vertical Bending Moment at Midships Versus Nominal Hourly, Nominal Seaway and Load Cycle Exceedence Probabilities

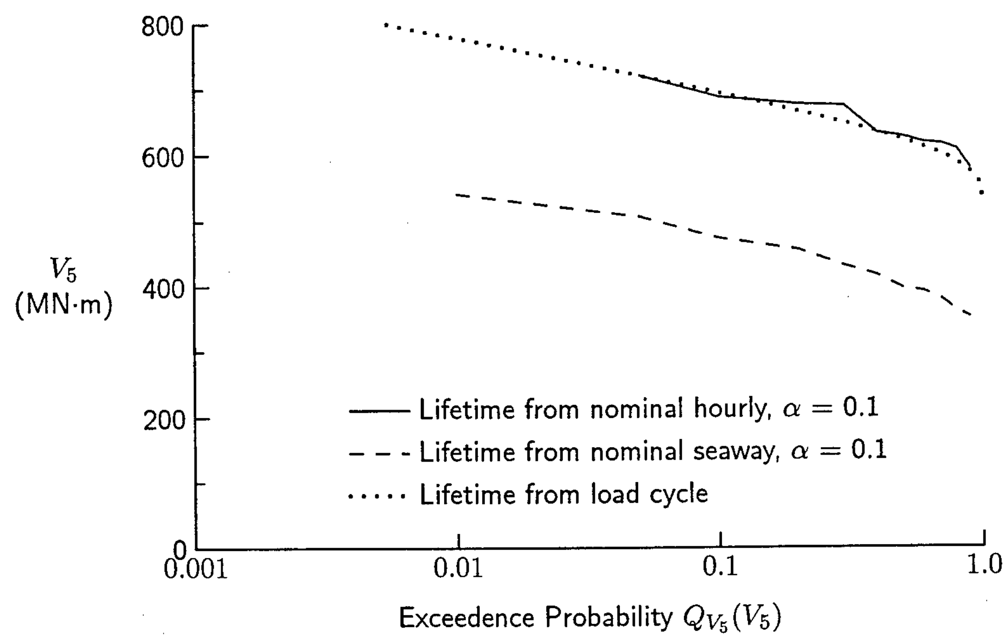

Figure 2: Vertical Bending Moment at Midships Versus Lifetime Exceedence Probability

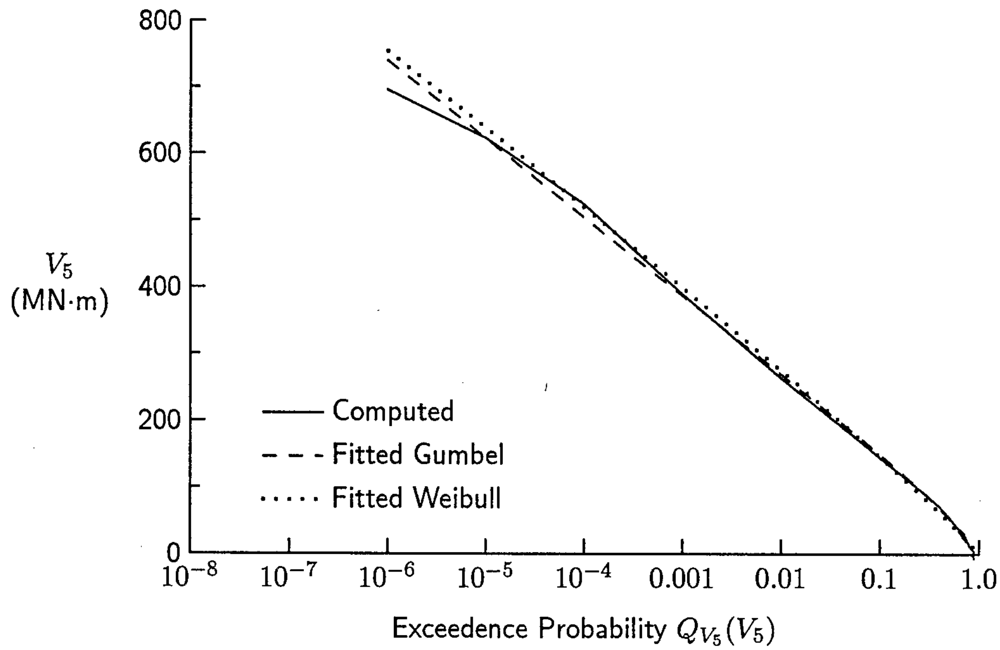

Figure 3: Computed and Fitted Distributions for Nominal Hourly Vertical Bending Moment at Midships, $\alpha = 0.1$

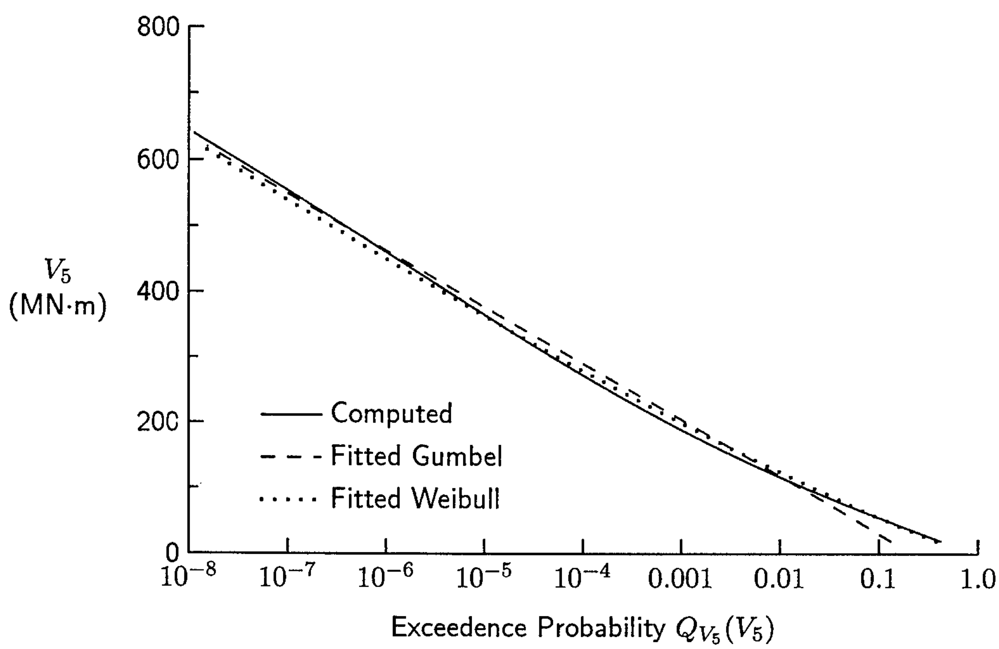

Figure 4: Computed and Fitted Distributions for Load Cycle Vertical Bending Moment at Midships

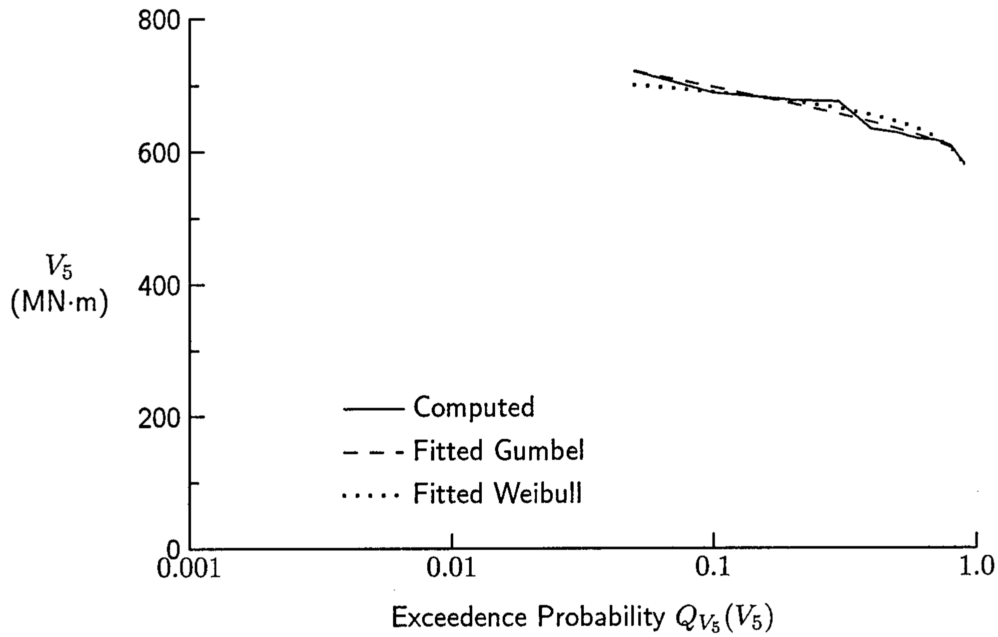

Figure 5: Computed and Fitted Distributions for Lifetime Vertical Bending Moment at Midships from Nominal Hourly Loads, $\alpha = 0.1$

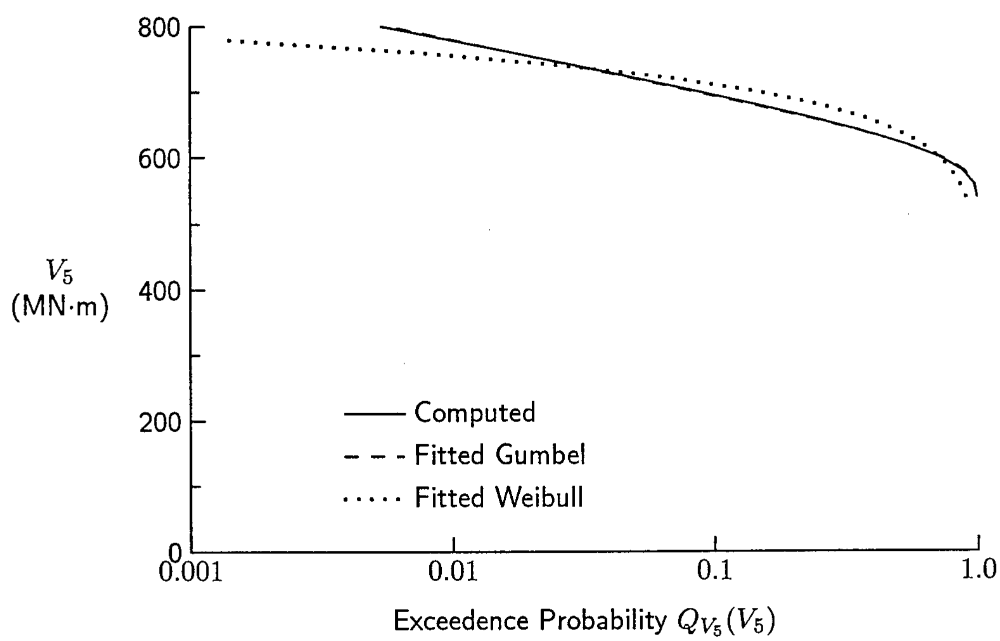

Figure 6: Computed and Fitted Distributions for Lifetime Vertical Bending Moment at Midships from Load Cycles

Table 2: Mean and Standard Deviation Values for Vertical Bending Moment at Midships

Description	Mean (MN·m)	Standard deviation (MN·m)
Nominal hourly, $\alpha = 0.1$ (Weibull)	66.1	60.5
Load cycle amplitude (Weibull)	22.5	26.5
Lifetime maximum from hourly, $\alpha = 0.1$ (Gumbel)	641.2	42.7
Lifetime maximum from cycle (Gumbel)	631.2	47.2

Figures 7 to 9 give conditional probabilities for ship heading, wave period, and wave height when vertical bending moment has an amplitude greater than 600 MN·m. These figures indicate which conditions are predominant for large vertical bending moments. Not surprisingly, the large vertical bending moments are most likely to be caused by head seas and large waves. The most likely wave periods for large vertical bending moments are associated with relatively steep waves.

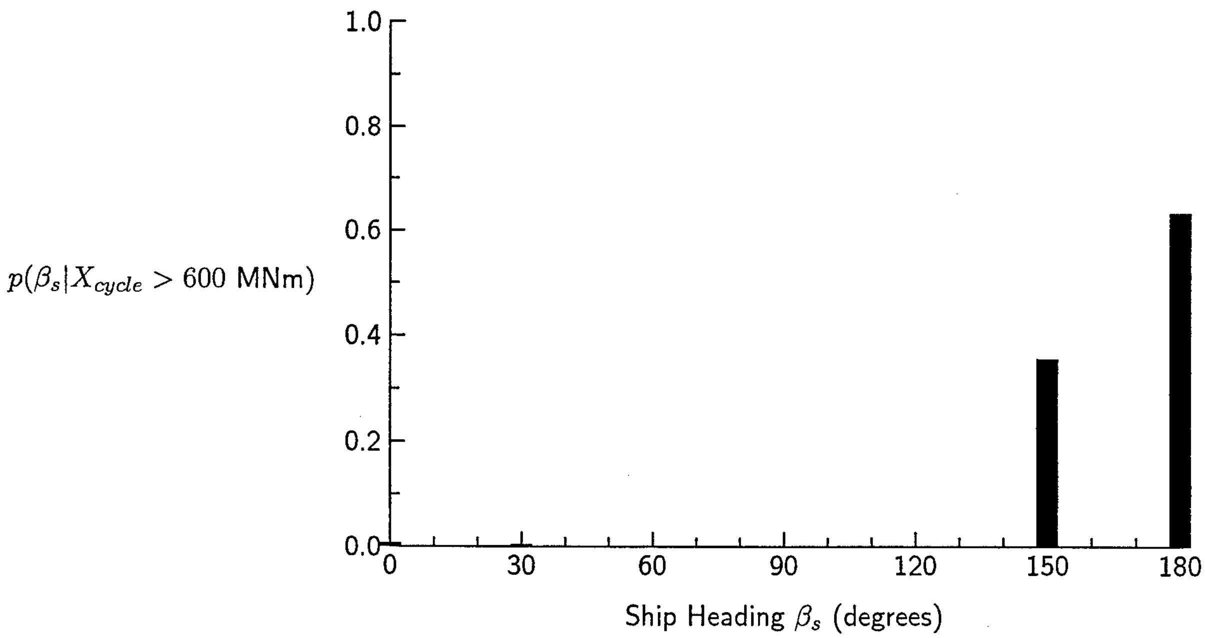

Figure 7: Conditional Probability of Heading Given Vertical Bending Moment Amplitude Greater than 600 MN·m

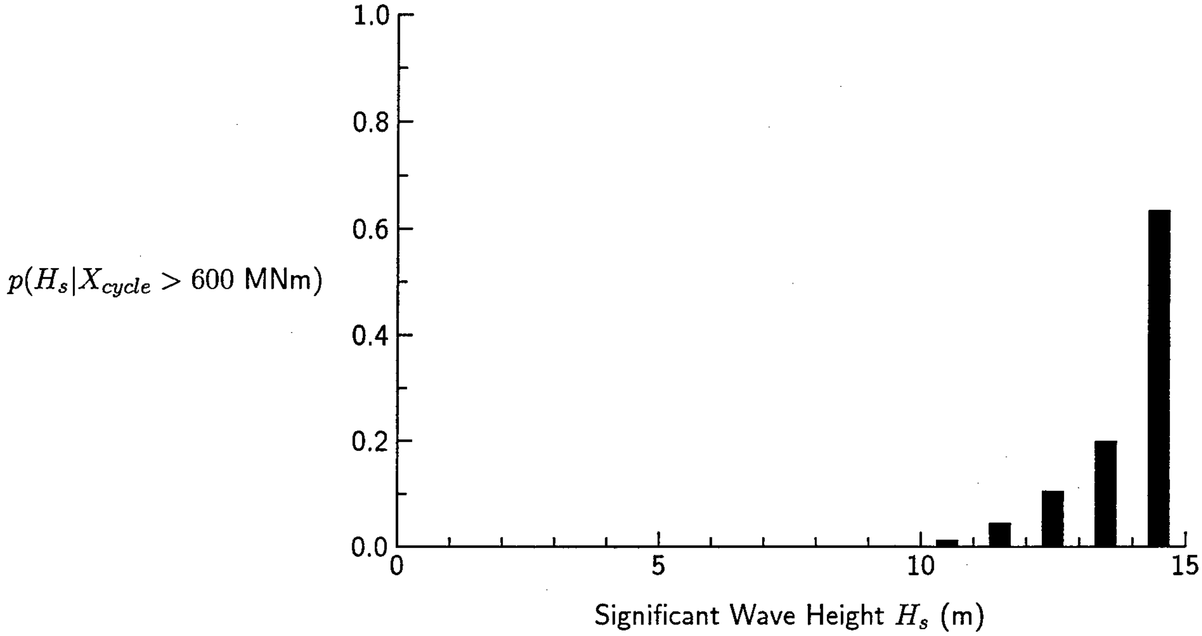

Figure 8: Conditional Probability of Significant Wave Height Given Vertical Bending Moment Amplitude Greater than 600 MN·m

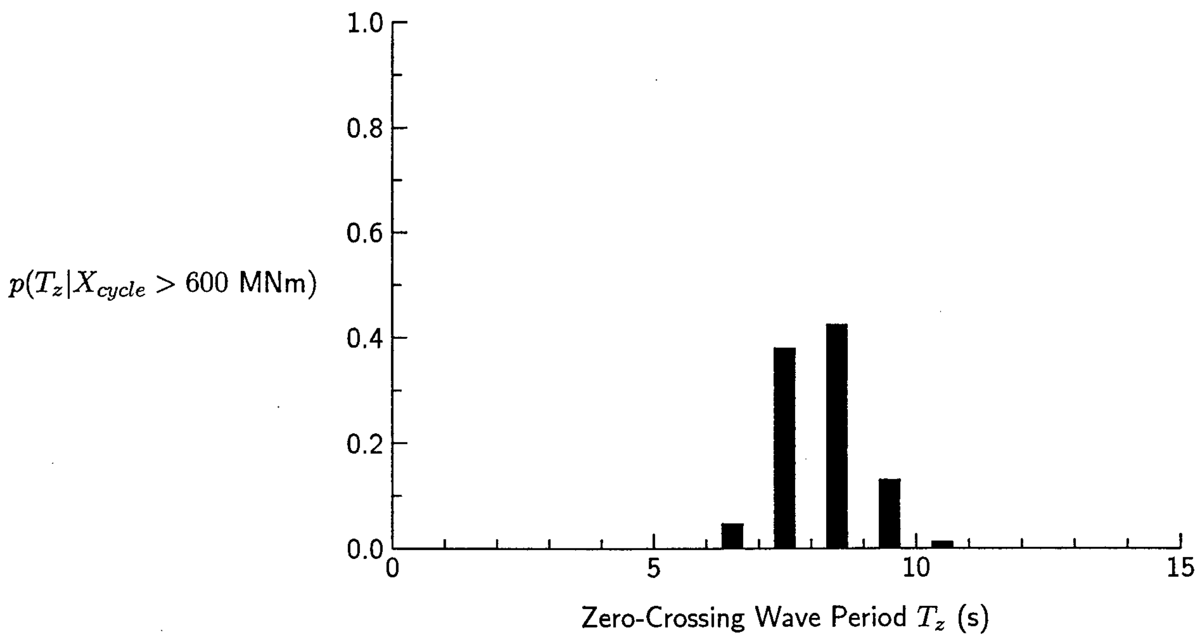

Figure 9: Conditional Probability of Zero-Crossing Wave Period Given Vertical Bending Moment Amplitude Greater than 600 MN·m

7.2 Horizontal Bending Moment at Midships

Figures 10 to 15 show horizontal bending moment at midships versus exceedence probability. The general trends are essentially the same as for vertical bending moment. The lifetime exceedence probabilities are essentially the same for the nominal hourly maximum and load cycle approaches when the nominal hourly exceedence probability α is set to 0.1. As was observed for vertical bending moment, the nominal seaway maximum approach predicts significantly smaller lifetime loads than the other two approaches.

The Weibull distribution provides good fits to exceedence probabilities for nominal hourly maximum and load cycle values; however, the Gumbel distribution provides superior matching to lifetime exceedence probabilities.

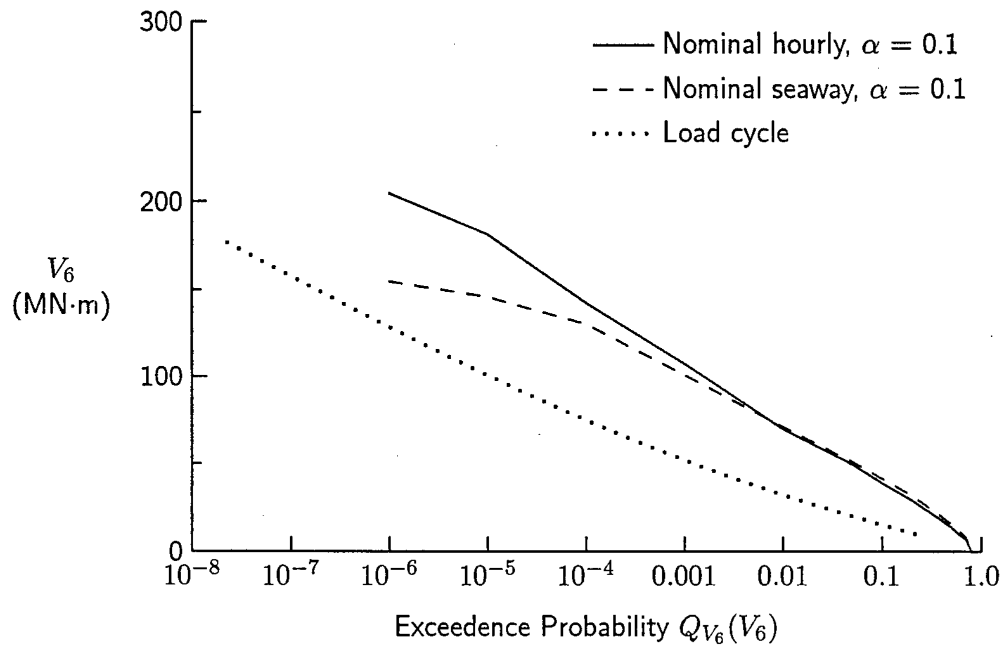

Figure 10: Horizontal Bending Moment at Midships Versus Nominal Hourly Maximum and Load Cycle Exceedence Probabilities

Table 3 gives means and standard deviations based on fitted distributions. The values of the horizontal bending moment parameters are approximately one third of the values for vertical bending moment. Based on the lifetime maximum parameters and a probability of exceedence of $\delta = 0.01$, the design horizontal bending moment at midships would be approximately 235 MN·m.

Figures 16 to 18 give conditional probabilities for ship heading, wave period, and wave height when horizontal bending moment has an amplitude greater than 180 MN·m. Largest horizontal bending moments are most likely to occur at headings of 60 and 120 degrees, which are both 30 degrees off beam seas. As expected, significant wave heights are likely to be large for large bending moments. The conditional distribution of wave periods indicates that steep waves are dominant for high horizontal bending moments.

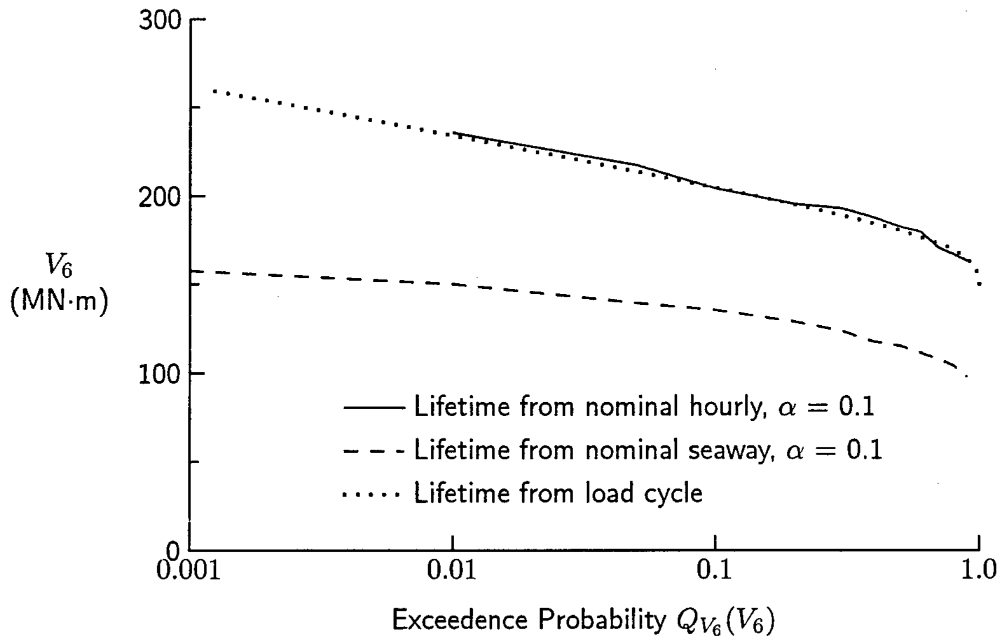

Figure 11: Horizontal Bending Moment at Midships Versus Lifetime Exceedence Probability

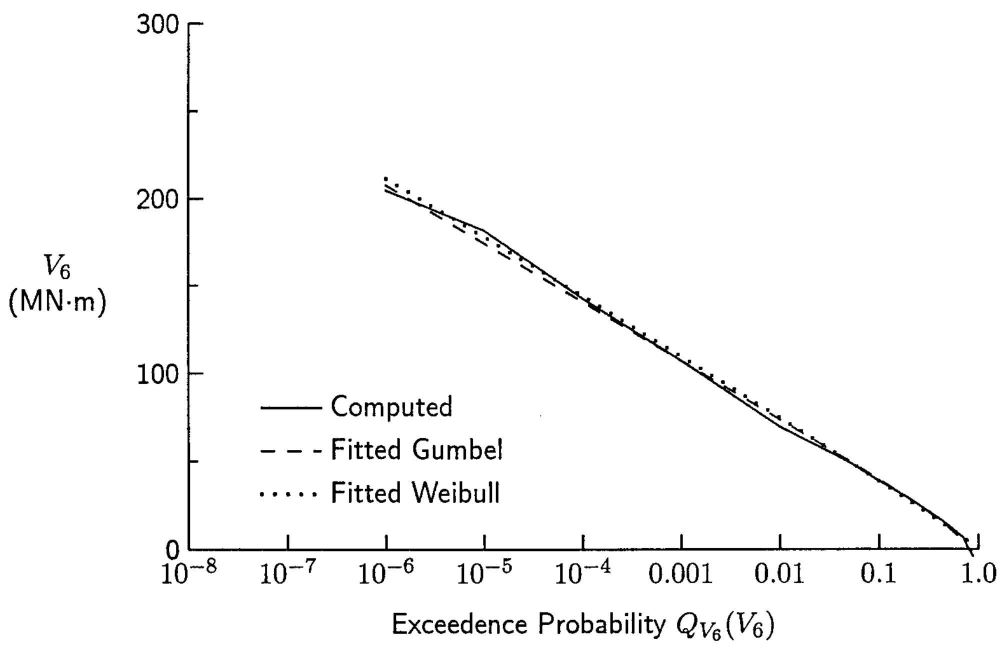

Figure 12: Computed and Fitted Distributions for Nominal Hourly Maximum Horizontal Bending Moment at Midships, $\alpha = 0.1$

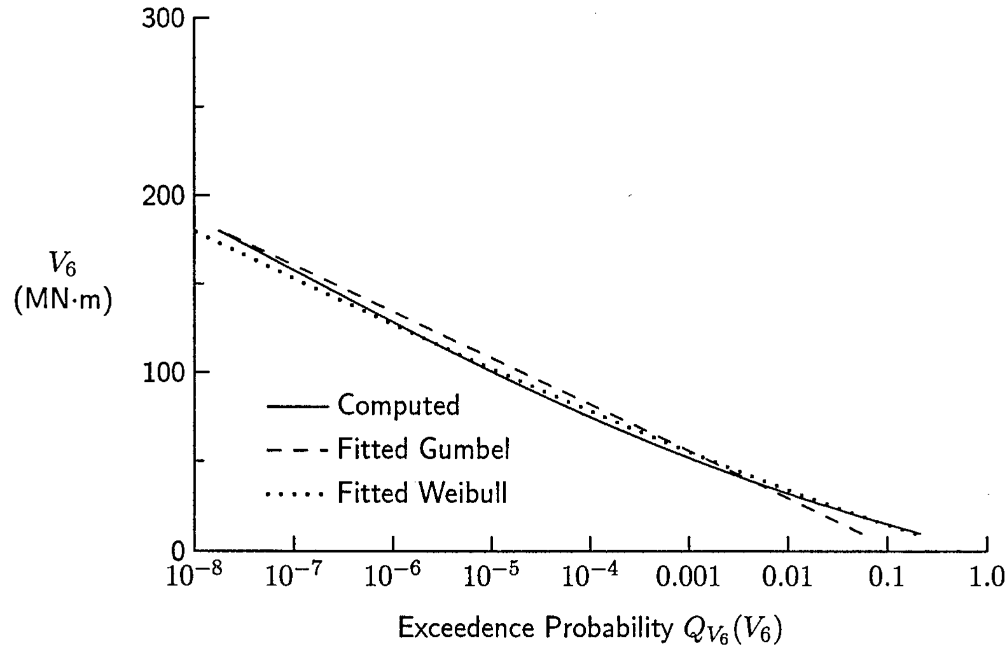

Figure 13: Computed and Fitted Distributions for Load Cycle Horizontal Bending Moment at Midships

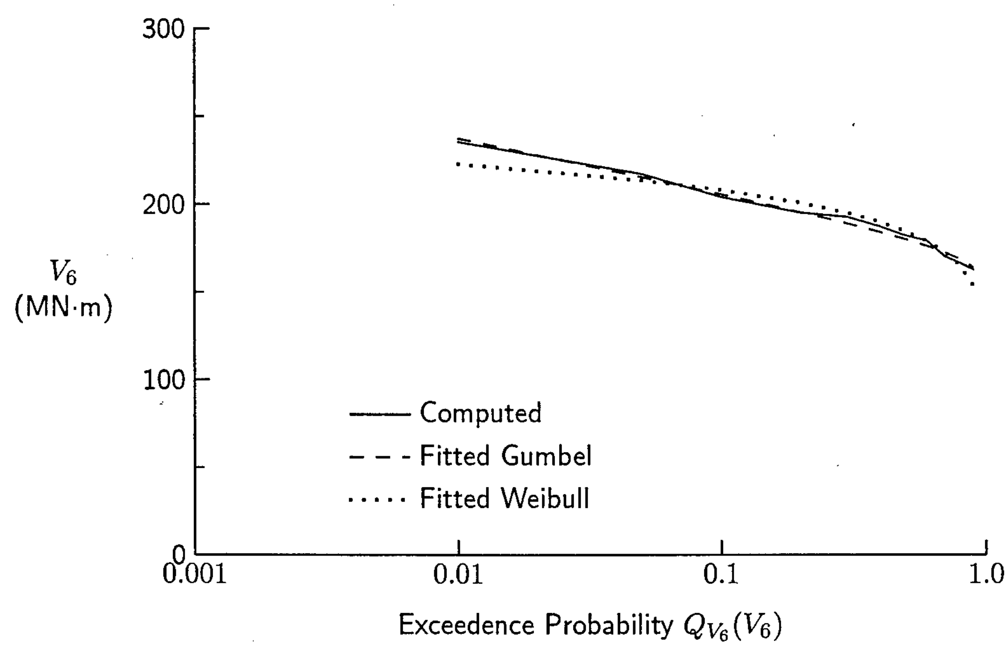

Figure 14: Computed and Fitted Distributions for Lifetime Horizontal Bending Moment at Midships from Nominal Hourly Loads, $\alpha = 0.1$

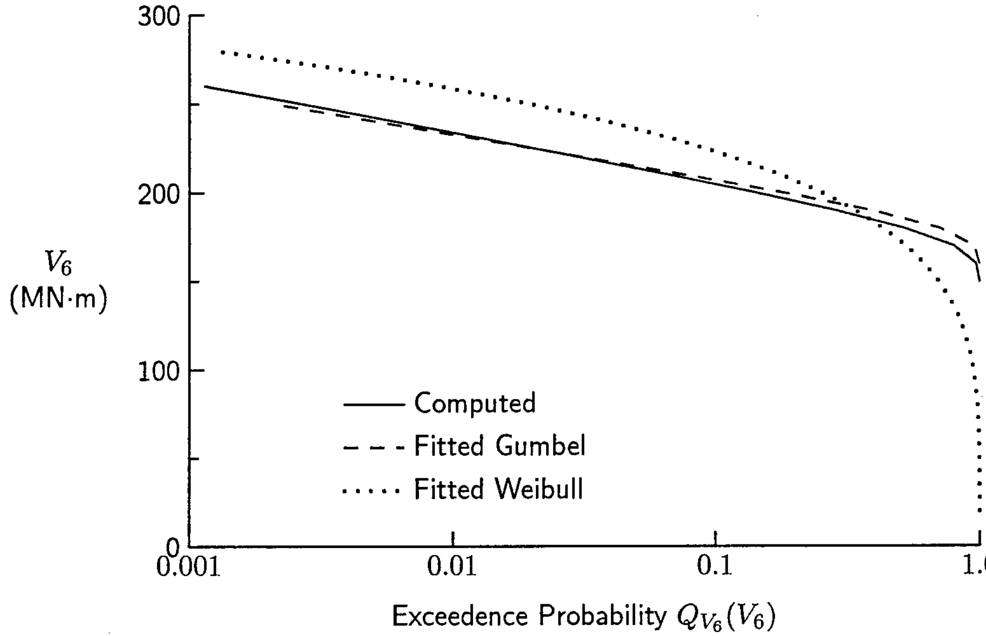

Figure 15: Computed and Fitted Distributions for Lifetime Horizontal Bending Moment at Midships from Load Cycles

Table 3: Mean and Standard Deviation Values for Horizontal Bending Moment at Midships

Description	Mean (MN·m)	Standard deviation (MN·m)
Nominal hourly maximum, $\alpha = 0.1$ (Weibull)	17.3	16.4
Load cycle amplitude (Weibull)	6.0	7.23
Lifetime maximum from hourly, $\alpha = 0.1$ (Gumbel)	183.4	17.3
Lifetime maximum from cycle (Gumbel)	188.6	14.1

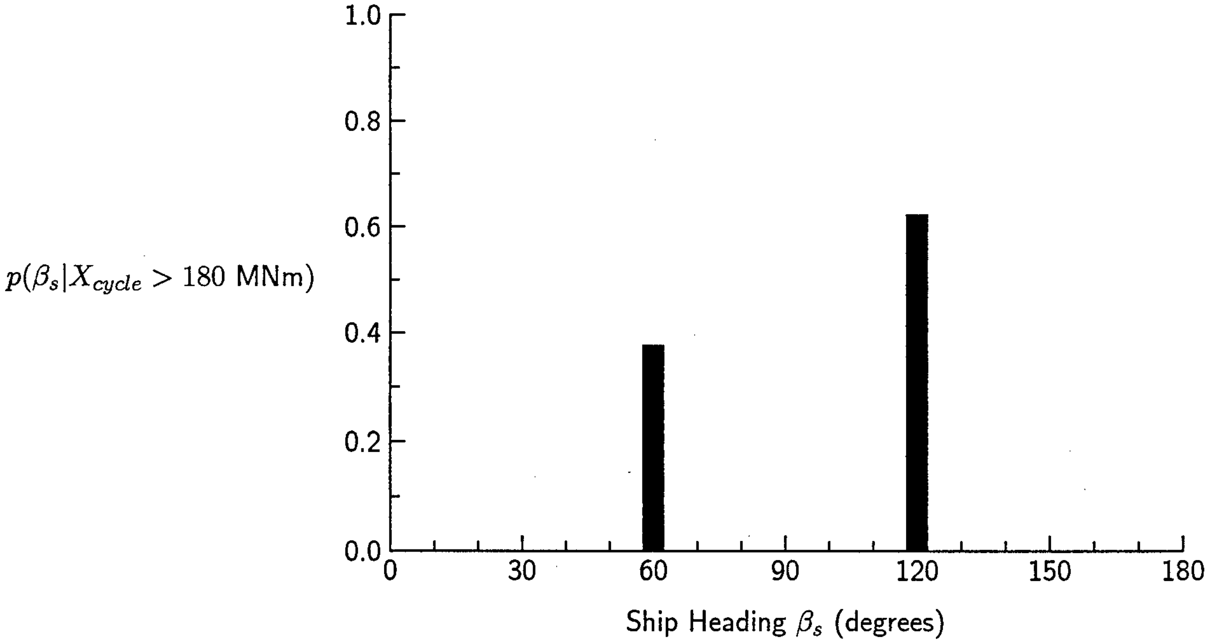

Figure 16: Conditional Probability of Heading Given Horizontal Bending Moment Amplitude Greater than 180 MN·m

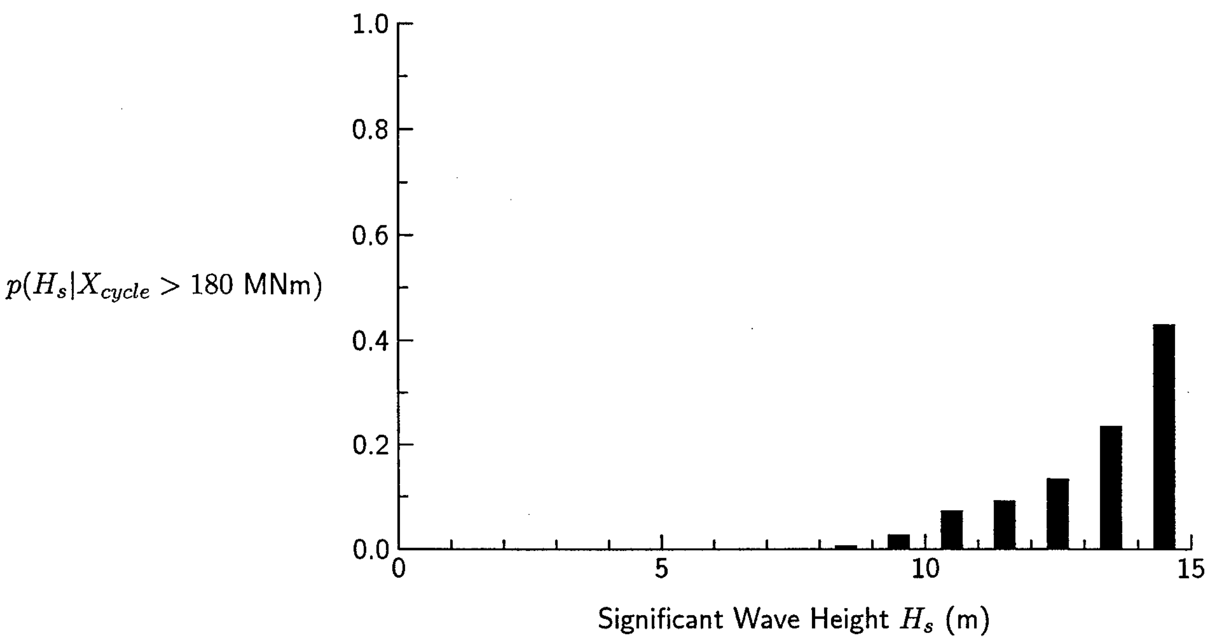

Figure 17: Conditional Probability of Significant Wave Height Given Horizontal Bending Moment Amplitude Greater than 180 MN·m

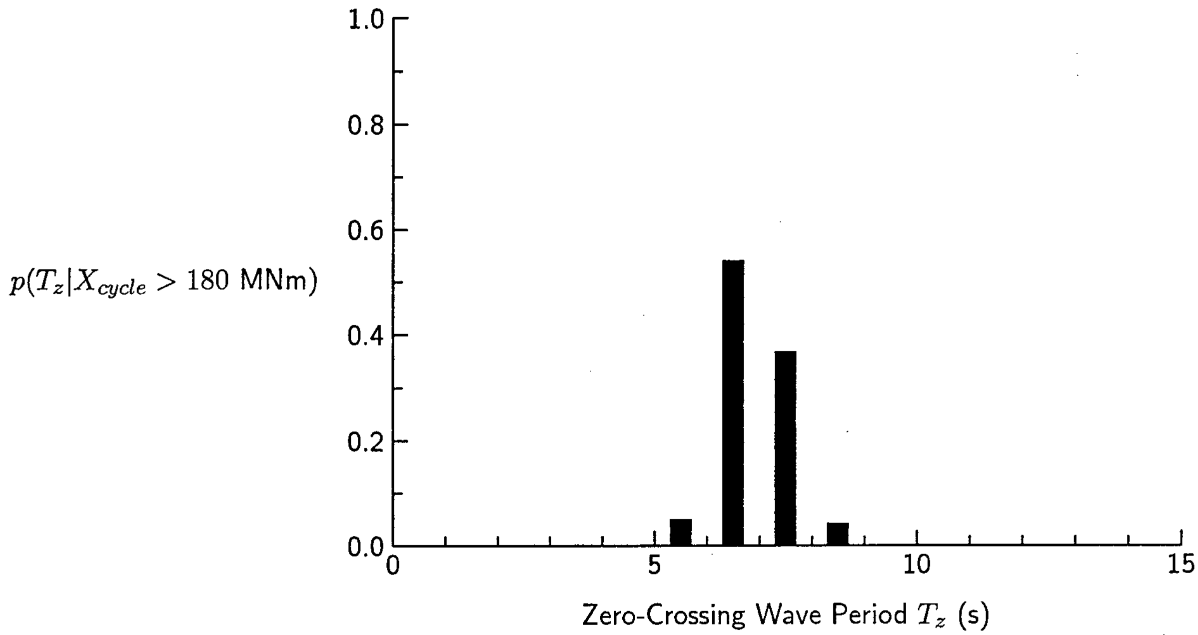

Figure 18: Conditional Probability of Zero-Crossing Wave Period Given Horizontal Bending Moment Amplitude Greater than 180 MN·m

8 Recommendations for Future Work

The present study represents an initial phase for computing design loads for ships, and can form the basis for more sophisticated analysis. This section describes several areas that should be considered to obtain more accurate design wave loads.

8.1 Wave Scattergrams for Ship Missions

The example case in the present study considers a ship in a single operational area. A more realistic analysis should use a composite wave scattergram based on the areas and seasons in which the ship will be operational. Derivation of composite scattergrams is a relatively simple procedure. DREA intends to develop software that will produce composite scattergrams based on BMT Global Wave Statistics. Saving the Global Wave Statistics database in accessible format is the biggest task of this development and is currently underway.

8.2 Correlations between Wave Conditions and Ship Operations

The present study neglects correlations between wave conditions and ship operations. In reality, ship operations can be greatly influenced by wave conditions, particularly in severe seas. For example, a ship captain will reduce speed in severe seas to reduce the incidence of slamming. Linear wave loads appear to have moderate dependence on ship speed and large dependence on ship heading. For nonlinear wave loads such as slamming, they can be greatly dependent on both ship speed and heading; thus, correlations between wave conditions and ship operations must be considered. Ship logs can be used to determine the influence of wave conditions on ship operations.

8.3 Three Dimensional Hydrodynamic Effects

Load computations for the CPF [7, 11] have shown that strip theory overpredicts vertical bending moment at midships by approximately 30 percent, while the three dimensional code PRECAL gives better results, particularly at lower ship speeds. The wide transom stern of the CPF necessitates use of three dimensional hydrodynamic coefficients for the accurate prediction of sea loads.

8.4 Nonlinear Wave Loads

Nonlinear effects can significantly influence wave loads, particularly for severe conditions which are of greatest interest for design. Important nonlinear effects include non-zero mean wave loads, sag/hog ratios greater than unity, green seas, and slamming. Experiments for the CPF reported in Reference 11 indicate that slamming loads are very important but that non-zero mean wave loads are less important.

Guedes Soares and Schellin [3] and Jensen and Dogliani [4] give frequency domain approaches for predicting wave loads based on nonlinear strip theory. Alternatively, Shin et al. [12] and Sclavounos et al. [13] give time domain approaches for computing nonlinear sea loads. The frequency domain approaches have the advantages of being computationally efficient and directly producing statistical information. If a nonlinear frequency domain approach were to be used for

the CPF, strip theory would likely be inadequate because of significant three dimensional hydrodynamic effects. Time domain approaches are likely more suitable for predicting transient loads from Green seas and slamming. Due to difficulties with time domain predictions, verification with frequency domain predictions and experiments is usually necessary.

8.5 Wave Data for Large Wave Heights

The sample computations in the previous section indicate that the design lifetime sea loads for the CPF will be associated with significant wave heights of the order of 15 m. Accurate probability distributions are needed for wave heights associated with design conditions; however, BMT Global Wave Statistics has the limitation of a single wave height range for significant wave heights above 14 m. Improved modelling of wave height distributions could likely be achieved by fitting distributions to the upper wave height ranges of the BMT data. Alternatively, Reference 14 gives distributions for wave height extremes based on observed storm data. McTaggart [15] applied extreme wave data to prediction of ship capsize in waves.

9 Conclusions

Three methods have been successfully developed for predicting sea load exceedence probabilities based upon linear theory. Although the nominal hourly and nominal seaway approaches are useful, the load cycle approach appears to be superior because it fully considers both short-term and long-term variations of sea loads.

For fatigue computations, the load cycle approach gives required exceedence probabilities for individual load cycles. The nominal hourly, nominal seaway, and load cycle approaches all give lifetime exceedence probabilities for sea loads; however, the nominal hourly and nominal seaway load approaches require that the user select an exceedence probability for hourly and seaway maximum loads. All three computational approaches can yield information regarding conditions associated with design events.

Sample computations for the CPF demonstrate that the approaches can be used to determine probability distributions for sea loads. The nominal seaway approach appears to significantly underpredict lifetime loads because the expected exposure times for extreme conditions were found to be short. Gumbel distributions provide very good fits to computed exceedence probabilities for lifetime vertical and horizontal bending moments. For individual load cycles and nominal hourly maxima, Weibull distribution give good fits to computed exceedence probabilities. For maximum lifetime horizontal and vertical bending moments for the CPF, the most likely significant wave height will be approximately 15 m.

The current linear analysis could form the basis for more sophisticated approaches. Development of composite wave scattergrams for mission and lifetime profiles will likely be an easy task. Correlations between wave conditions and ship operations are likely very important for severe conditions and should be considered. Three dimensional hydrodynamic effects are important for the CPF and can be included using codes such as PRECAL. Nonlinear effects, which can be very important in severe seas, could be determined using nonlinear codes in the frequency or time domains. While time domain codes offer better potential for transient effects such as slamming and green seas, they are still evolving for application to design.

A EXTRMLIN Input

A.1 Input Records

Detailed descriptions of EXTRMLIN input records are given below. Appendix A.2 gives sample input for vertical bending moment of the Canadian Patrol Frigate. Each new input record or sub-record corresponds to a new file line. The format of the input file may be adjusted by inserting extra blanks between any numerical data, and by placing data from within any particular record on separate lines; however, separate records cannot be combined on a single line.

Record (a), Eighty Character Title
TITLE (columns 1 - 80)

TITLE Alphanumeric title (maximum of 80 characters) which is written on output.

Record (b), SHIPMO7 Post-processing File
SMPPRFILE (columns 1-30)

SMPPRFILE Name of SHIPMO7 binary post-processing file (maximum 30 characters). This file must have metric output units (OUTSYS = METRIC).

Record (c), BMT Global Wave Statistics Wave Scattergram File
WSFILE (columns 1-30)

WSFILE Name of wave scattergram file (maximum 30 characters). The scattergram file has joint observations of significant wave height and wave period in BMT Global Wave Statistics ASCII format.

Record (d), Number of Ship Speeds
NSPEED (1 integer)

NSPEED Number of ship speeds. This must correspond to the number of ship speeds NSPEED in the SHIPMO7 post-processing file.

Record (d1), Ship Speeds and Probabilities
SPDKNOT(I), PSPEED(I) (NSPEED records of 2 reals)

SPDKNOT(I) Ship speed in knots. This must correspond to ship speed SPDKNOT(I) in the SHIPMO7 post-processing file.

PSPEED(I) Probability of ship travelling at speed SPDKNOT(I). The PSPEED(I) values should have a sum of 1.0.

Record (e), Number of Sea Directions
NSEADIR (1 integer)

NSEADIR Number of sea directions. This must correspond to the number of ship speeds NSEADIR in the SHIPMO7 post-processing file.

Record (e1), Sea Directions and Probabilities
SEADIR(I), PSEADIR(I) (NSEADIR records of 2 reals)

SEADIR(I) Sea direction (from) relative to ship heading (degrees). This must correspond to sea direction SEADIR(I) in the SHIPMO7 post-processing file.

PSEADIR(I) Probability of waves approaching ship from direction PSEADIR(I). The sum of the PSEADIR(I) values should equal 1.0.

Record (f), Exceedence Probability of Nominal Load in One Hour Seaway and Variable Duration Seaway
PMAXSEAWAY (1 real)

PMAXSEAWAY Probability of exceedence for nominal maximum load in one hour seaway and variable duration seaway.

Record (g), Sea Load Mode
LOADMODE (1 character string)

LOADMODE Control string for sea load mode. The five possible inputs are:

HORSHEAR	Horizontal shear force.
VERTSHEAR	Vertical shear force.
TORSION	Torsional moment.
VERTBEND	Vertical bending moment.
HORBEND	Horizontal bending moment.

Record (h), Station for Sea Loads
STATION (1 real)

STATION Station for sea loads. The station must correspond to a station XSTLOAD(I) in the SHIPMO7 post-processing file.

Record (i), Ship Life and Fraction of Life Spent at Sea
SHIPLIFE, PATSEA (2 reals)

SHIPLIFE Total ship life (years).

PATSEA Fraction of ship life spent at sea.

Record (j), Probability Range for Fitting Distributions
PEXMINFIT, PEXMAXFIT (2 reals)

PEXMINFIT Lower limit on exceedence probability for fitting Gumbel and Weibull distributions to computed exceedence probabilities.

PEXMAXFIT Upper limit on exceedence probability for fitting Gumbel and Weibull distributions to computed exceedence probabilities.

Record (k), Increment and Maximum of Output Load Cycle Amplitudes
XCYCLEINC, XCYCLEMAX (2 reals)

XCYCLEINC Increment of output load cycle amplitudes (MN or MN·m).

XCYCLEMAX Maximum output load cycle amplitude (MN or MN·m).

Record (l), Lower Threshold of Load Cycle Amplitude for Conditional Probabilities
XCYCLECOND (1 real)

XCYCLECOND Lower threshold of load cycle amplitude for conditional probabilities of ship speed, heading, and wave conditions (N or N·m).

A.2 Sample Input

```
Midships vertical bending moment for CPF  <--- Record (a) Title
cpfextreme.ppr                            <--- Record (b) SHIPM07 file
area15.gwa                                <--- Record (c) Wave statistics file
2                                         <--- Record (d) Number of ship speeds
10.0 0.5                                  <--- Record (d1) Speed, probability
18.0 0.5                                  <--- Record (d1)
7                                         <--- Record (e) Number of headings
0.0 0.08325                               <--- Record (e1) Heading, probability
30.0 0.1667                               <--- Record (e1)
60.0 0.1667                               <--- Record (e1)
90.0 0.1667                               <--- Record (e1)
120.0 0.1667                              <--- Record (e1)
150.0 0.1667                              <--- Record (e1)
180.0 0.08325                             <--- Record (e1)
0.1                                       <--- Record (f) Hourly P(exceed)
VERTBEND                                  <--- Record (g) Mode
10.0                                      <--- Record (h) Station number
30.0 0.3                                  <--- Record (i) Life, fraction at sea
0.0 0.9                                   <--- Record (j) Fit probability range
20.0 800.0                                <--- Record (k) Cycle inc and max
600.0                                     <--- Record (l) Conditional threshold
```

B EXTRMLIN Output

B.1 Description of Output

Appendix B.2 gives sample computations for vertical bending moment of the Canadian Patrol Frigate. The output begins with user input values, which are followed by the wave scattergram. The wave scattergram values are given as number per million observations, which corresponds with the resolution of the BMT Global Wave Statistics database. Due to rounding error, a correction factor must be applied to the wave scattergram data to ensure that the sum of probabilities is equal to one. The output also gives information from the SHIPMO7 post-processing file.

The first set of output computations is for nominal hourly maximum loads. The output gives nominal hourly sea loads and conditions for ranked events associated with various exceedence probabilities. A second table gives exceedence probabilities and conditions for the highest ranked load events. The output then gives statistical fits for both nominal hourly maximum and lifetime maximum sea loads. After the nominal hourly sea loads, the output has similar computation results for the nominal seaway sea loads.

The third set of output computations is for load cycle amplitudes. Load cycle and lifetime exceedence probabilities are given for load levels requested by the user. Subsequent output gives statistical fits to load cycle and lifetime maximum loads. The output finishes with conditional probabilities for ship and sea conditions when loads exceed an input threshold level.

B.2 Sample Output

```
Output from program EXTRMLIN, Risk analysis of loads using linear theory
Defence Research Establishment Atlantic
Program Version 1.0 - January 1998

EXTRMLIN Run Title:
Midships vertical bending moment for CPF
11:27:23 08-May-98


***************  ECHO OF USER INPUT  ***************

SHIPMO7 post-processing file :    cpfextreme.ppr
BMT Global Wave Statistics file : area15.gwa

 2 ship speeds
Speed (kt)   P(Speed)
 10.00         .500
 18.00         .500
             -------
              1.000

 7 ship headings
Heading (deg)   P(Heading)
   .00         .083
 30.00         .167
 60.00         .167
 90.00         .167
120.00         .167
150.00         .167
180.00         .083
             -------
              1.000

Probability of exceedence for nominal maximum load in 1 hour seaway :     .1000

Load mode : VERTBEND
Ship station for load computation :   10.0000
Ship life (years) :      30.00

Fraction of life at sea :      .3000


Minimum probability of exceedence for fitting distributions : .000000E+00
Maximum probability of exceedence for fitting distributions :     .900000

Load cycle parameters (input units MN or MNm)
Load increment          :   20.000
Maximum load            :  800.000
Conditional design load :  600.000
```

**************** Echo of BMT Global Wave Statistics Wave Scattergram ****************

File name	: area15.gwa
Date and time record created	: 10/10/1997 8:39:29
Sea area number	: 15
Season number	: 0
Months	: January to December
Direction number	: 0
Percentage of obs for area	: 100.000
Directions	: .0 to 360.0
Direction label	: ALL DIRECTIONS

Number of observations per million

	Wave Period Tz (s)										
Hs (m)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
.5	195	5148	22478	31077	18074	5512	1059	147	16	2	
1.5	6	1241	20714	71775	86236	49613	16978	4018	730	110	14
2.5		230	7349	43695	83798	72651	35743	11681	2838	555	93
3.5		45	2203	18702	49097	56350	35688	14653	4377	1034	205
4.5		9	631	6984	23184	32851	25176	12298	4304	1175	267
5.5		2	181	2480	9923	16639	14855	8342	3316	1018	257
6.5		1	54	876	4092	7893	8001	5046	2232	756	209
7.5			17	316	1683	3659	4136	2881	1396	514	154
8.5			5	118	704	1700	2113	1605	842	334	107
9.5			2	46	303	803	1085	890	502	212	72
10.5			1	19	135	388	566	497	299	134	48
11.5				8	62	192	300	281	179	85	32
12.5				3	29	97	162	161	108	54	21
13.5				2	14	51	89	93	66	34	14
14.5				1	15	58	115	134	105	61	28

Correction factor applied to wave scattergram : .999878

```
******************* Echo of SHIPMO7 Post-processing File *******************

 File  : cpfextreme.ppr
 Title : Extreme load prediction example - CPF
                                        16-APR-98 10:51:04
 Units : METRIC
 Spectrum : BRETSCHNEIDER

 Ship characteristics
      Length            :   124.500 m
      Displacement      :    4731.8 tonnes
      LCB aft of FP     :    64.553 m
      Draft at midships :     5.025 m
      Trim by stern     :     -.135 m
      KG                :     6.230 m
      Beam at midships  :    14.803 m
```

**** Nominal hourly maximum loads ****

P(exceed)		Vertical bending moment			Ship conditions		Wave conditions	
Life	Hour	Max (MNm)	RMS (MNm)	Tz (s)	Speed (kt)	Head (deg)	Hs (m)	Tz (s)
.057	.000001	703.1	166.8	5.0	18.0	150.0	14.0	6.5
.563	.000010	619.9	147.6	5.3	18.0	180.0	12.0	7.5
1.000	.000103	522.4	124.9	5.7	18.0	180.0	12.0	9.5
1.000	.000991	390.2	93.8	6.2	10.0	150.0	9.0	7.5
1.000	.009721	264.4	67.1	15.4	10.0	.0	13.0	13.5
1.000	.049942	181.9	43.6	5.9	10.0	150.0	4.0	6.5
1.000	.100924	145.3	34.6	5.3	18.0	150.0	3.0	7.5
1.000	.200888	109.8	28.5	21.6	18.0	30.0	4.0	9.5
1.000	.299333	88.4	22.4	15.0	10.0	.0	3.0	10.5
1.000	.400456	71.8	18.0	12.5	18.0	60.0	3.0	9.5
1.000	.500437	56.6	13.5	5.6	10.0	120.0	2.0	7.5
1.000	.597382	41.7	9.9	5.1	18.0	90.0	14.0	9.5
1.000	.699032	33.1	7.9	5.4	10.0	90.0	12.0	9.5
1.000	.800062	12.7	3.0	4.7	18.0	90.0	3.0	7.5
1.000	.897142	3.9	.9	5.7	18.0	90.0	2.0	12.5
1.000	.949297	.0	.0	5.9	10.0	150.0	.0	6.5
1.000	.990254	.0	.0	13.0	10.0	30.0	.0	7.5

**** Highest nominal hourly maximum loads for observed conditions ****

P(exceed)		Vertical bending moment			Ship conditions		Wave conditions	
Life	Hour	Max (MNm)	RMS (MNm)	Tz (s)	Speed (kt)	Head (deg)	Hs (m)	Tz (s)
.048	.000001	723.2	172.2	5.3	18.0	180.0	14.0	7.5
.051	.000001	718.9	170.6	5.0	18.0	180.0	14.0	6.5
.057	.000001	703.1	166.8	5.0	18.0	150.0	14.0	6.5
.146	.000002	678.2	161.4	5.3	18.0	150.0	14.0	7.5
.294	.000004	675.6	161.2	5.5	18.0	180.0	14.0	8.5
.326	.000005	671.5	159.9	5.3	18.0	180.0	13.0	7.5
.330	.000005	667.5	158.4	5.0	18.0	180.0	13.0	6.5
.339	.000005	652.9	154.9	5.0	18.0	150.0	13.0	6.5
.341	.000005	652.5	156.5	6.1	10.0	180.0	14.0	6.5
.373	.000006	649.2	156.2	6.4	10.0	180.0	14.0	7.5
.377	.000006	636.6	152.5	5.9	10.0	150.0	14.0	6.5
.431	.000007	629.8	149.9	5.3	18.0	150.0	13.0	7.5
.519	.000009	627.4	149.7	5.5	18.0	180.0	13.0	8.5
.563	.000010	619.9	147.6	5.3	18.0	180.0	12.0	7.5
.701	.000015	616.7	147.1	5.5	18.0	150.0	14.0	8.5
.704	.000015	616.2	146.2	5.0	18.0	180.0	12.0	6.5
.797	.000020	609.5	145.7	5.7	18.0	180.0	14.0	9.5
.816	.000021	607.0	145.8	6.2	10.0	150.0	14.0	7.5
.817	.000022	605.9	145.3	6.1	10.0	180.0	13.0	6.5
.849	.000024	602.9	145.4	6.6	10.0	180.0	14.0	8.5

```
**** Fitted distributions of nominal hourly maximum load ****

Vertical bending moment
Weibull distribution
Hourly P(exceed) = exp(-(x/k)**beta)
Weibull k (MNm) :   68.2213
Weibull beta    :    1.0921

Mean            :   65.9863 (MNm)
Std deviation   :   60.4876 (MNm)

GUMBEL distribution
Hourly P(exceed) = 1 - exp(-(exp(-alpha(x - u)))
GUMBEL u (MNm) :   35.3468
GUMBEL alpha (/MNm) :     .0196

Mean            :   64.7899 (MNm)
Std deviation   :   65.4231 (MNm)
```

P(exceed)	Vertical bending moment		
	Observed (MNm)	Weibull (MNm)	Gumbel (MNm)
.000001	695.8	755.4	740.1
.000010	622.8	639.2	622.6
.000100	525.0	521.1	505.2
.001000	390.2	400.4	387.7
.010000	264.4	276.2	270.0
.050000	181.8	186.3	186.9
.100000	145.4	146.4	150.1
.200000	109.9	105.5	111.9
.300000	88.4	80.9	87.9
.400000	71.8	63.0	69.6
.500000	56.6	48.8	54.0
.600000	41.5	36.9	39.8
.700000	33.1	26.5	25.9
.800000	12.7	17.3	11.1
.900000	3.9	8.7	-7.2

```
**** Fitted distributions of lifetime maximum nominal hourly maximum load ****

Vertical bending moment
Weibull distribution
Hourly P(exceed) = exp(-(x/k)**beta)
Weibull k (MNm) :  657.8682
Weibull beta    :   17.7704

Mean            :  638.4595 (MNm)
Std deviation   :   44.3610 (MNm)

GUMBEL distribution
Hourly P(exceed) = 1 - exp(-(exp(-alpha(x - u)))
GUMBEL u (MNm) :  621.8691
GUMBEL alpha (/MNm) :     .0301

Mean            :  641.0717 (MNm)
Std deviation   :   42.6683 (MNm)
```

P(exceed)	Vertical bending moment Observed (MNm)	Weibull (MNm)	Gumbel (MNm)
.050000	720.4	699.8	720.7
.100000	688.3	689.5	696.7
.200000	677.1	675.7	671.8
.300000	674.8	664.8	656.2
.400000	633.6	654.6	644.2
.500000	627.9	644.4	634.1
.600000	619.0	633.5	624.8
.700000	616.8	620.8	615.7
.800000	609.1	604.6	606.0
.900000	580.2	579.6	594.1

**** Nominal seaway maximum loads ****

P(exceed) Life	Seaway	Vertical bending moment Max (MNm)	RMS (MNm)	Tz (s)	Ship conditions Speed (kt)	Head (deg)	Wave conditions Hs (m)	Tz (s)	Exposure time (hours)
.001	.000001	582.5	161.4	5.3	18.0	150.0	14.0	7.5	.10
.020	.000010	524.6	135.3	5.7	18.0	180.0	13.0	9.5	.29
.181	.000103	460.7	122.7	6.4	10.0	180.0	11.0	7.5	.20
.855	.000991	354.8	103.3	12.3	18.0	60.0	10.0	6.5	.12
1.000	.009721	261.4	115.2	27.0	18.0	.0	12.0	6.5	.01
1.000	.049942	189.6	67.3	22.4	18.0	30.0	8.0	5.5	.03
1.000	.100924	157.1	44.4	12.7	18.0	60.0	14.0	13.5	.18
1.000	.200888	119.4	33.6	6.0	10.0	120.0	13.0	13.5	.09
1.000	.299333	97.9	20.9	9.5	10.0	60.0	6.0	11.5	14.67
1.000	.400456	80.2	17.1	13.8	10.0	.0	2.0	5.5	24.11
1.000	.500437	62.1	12.0	12.5	18.0	60.0	2.0	9.5	234.85
1.000	.597382	43.9	14.4	4.6	10.0	90.0	13.0	6.5	.01
1.000	.699032	35.1	7.1	21.6	18.0	30.0	1.0	9.5	111.55
1.000	.800062	13.9	2.6	5.4	10.0	90.0	4.0	9.5	165.42
1.000	.897142	4.9	1.0	5.9	10.0	90.0	2.0	11.5	18.65
1.000	.949297	.0	.0	5.9	10.0	150.0	.0	6.5	204.19
1.000	.990254	.0	.0	13.0	10.0	30.0	.0	7.5	118.76

**** Highest nominal seaway maximum loads for observed conditions ****

P(exceed) Life	Seaway	Vertical bending moment Max (MNm)	RMS (MNm)	Tz (s)	Ship conditions Speed (kt)	Head (deg)	Wave conditions Hs (m)	Tz (s)	Exposure time Hours
.001	.000001	608.4	161.2	5.5	18.0	180.0	14.0	8.5	.19
.001	.000001	586.9	172.2	5.3	18.0	180.0	14.0	7.5	.05
.001	.000001	582.5	161.4	5.3	18.0	150.0	14.0	7.5	.10
.004	.000002	581.9	147.1	5.5	18.0	150.0	14.0	8.5	.38
.009	.000004	574.5	145.7	5.7	18.0	180.0	14.0	9.5	.38
.010	.000005	559.9	149.7	5.5	18.0	180.0	13.0	8.5	.17
.010	.000005	541.8	159.9	5.3	18.0	180.0	13.0	7.5	.05
.010	.000005	541.6	145.4	6.6	10.0	180.0	14.0	8.5	.19
.010	.000005	540.0	138.2	5.5	18.0	180.0	12.0	8.5	.32
.011	.000006	538.0	149.9	5.3	18.0	150.0	13.0	7.5	.09
.012	.000006	537.5	130.5	5.6	18.0	150.0	14.0	9.5	.76
.014	.000007	535.9	136.6	5.5	18.0	150.0	13.0	8.5	.34
.018	.000009	530.8	147.6	5.3	18.0	180.0	12.0	7.5	.10
.020	.000010	524.6	135.3	5.7	18.0	180.0	13.0	9.5	.29
.029	.000015	524.0	156.2	6.4	10.0	180.0	14.0	7.5	.05
.030	.000015	523.9	138.3	5.3	18.0	150.0	12.0	7.5	.19
.039	.000020	519.5	145.8	6.2	10.0	150.0	14.0	7.5	.10
.041	.000021	517.0	132.1	6.5	10.0	150.0	14.0	8.5	.38
.041	.000022	516.7	126.7	5.5	18.0	180.0	11.0	8.5	.63
.046	.000024	515.0	129.6	5.9	18.0	180.0	14.0	10.5	.44

```
**** Fitted distributions of nominal seaway maximum load ****

Vertical bending moment
Weibull distribution
Hourly P(exceed) = exp(-(x/k)**beta)
Weibull k (MNm) :   71.7517
Weibull beta    :    1.1460

Mean            :   68.3556 (MNm)
Std deviation   :   59.7931 (MNm)

GUMBEL distribution
Hourly P(exceed) = 1 - exp(-(exp(-alpha(x - u)))
GUMBEL u (MNm) :   48.6501
GUMBEL alpha (/MNm) :     .0223

Mean            :   74.5894 (MNm)
Std deviation   :   57.6376 (MNm)
```

P(exceed)	Vertical bending moment Observed (MNm)	Weibull (MNm)	Gumbel (MNm)
.000001	582.3	709.4	669.5
.000010	527.0	605.1	566.0
.000100	460.7	498.0	462.6
.001000	354.8	387.5	359.1
.010000	261.4	272.0	255.4
.050000	189.5	186.9	182.1
.100000	157.1	148.6	149.8
.200000	119.9	108.7	116.1
.300000	97.9	84.4	95.0
.400000	80.3	66.5	78.8
.500000	62.1	52.1	65.1
.600000	43.8	39.9	52.6
.700000	35.0	29.2	40.3
.800000	13.9	19.4	27.3
.900000	4.7	10.1	11.2

**** Fitted distributions of lifetime maximum nominal seaway maximum load ****

```
Vertical bending moment
Weibull distribution
Hourly P(exceed) = exp(-(x/k)**beta)
Weibull k (MNm) :  431.9839
Weibull beta    :    8.0046

Mean            :  406.8290 (MNm)
Std deviation   :   60.3287 (MNm)

GUMBEL distribution
Hourly P(exceed) = 1 - exp(-(exp(-alpha(x - u)))
GUMBEL u (MNm) :  388.2857
GUMBEL alpha (/MNm) :     .0272

Mean            :  409.4846 (MNm)
Std deviation   :   47.1045 (MNm)
```

P(exceed)	Vertical bending moment Observed (MNm)	Weibull (MNm)	Gumbel (MNm)
.010000	541.7	522.8	557.2
.050000	507.3	495.4	497.4
.100000	474.2	479.4	470.9
.200000	456.7	458.4	443.4
.300000	432.1	442.1	426.1
.400000	417.2	427.3	413.0
.500000	397.3	412.7	401.7
.600000	392.4	397.2	391.5
.700000	381.0	379.8	381.5
.800000	362.7	358.2	370.8
.900000	352.8	326.1	357.7

***** Fatigue load cycle computations ****

Vertical bending moment
Period for mean zero-crossing frequency: 7.18 seconds
Number of cycles during ship life : .395E+08

Load (MNm)	P(exceed) Cycle	Life	Cycles during life
20.000	.425933	1.000000	.168E+08
40.000	.186885	1.000000	.738E+07
60.000	.083012	1.000000	.328E+07
80.000	.038180	1.000000	.151E+07
100.000	.018266	1.000000	.722E+06
120.000	.009067	1.000000	.358E+06
140.000	.004652	1.000000	.184E+06
160.000	.002460	1.000000	.972E+05
180.000	.001336	1.000000	.528E+05
200.000	.000743	1.000000	.293E+05
220.000	.000422	1.000000	.167E+05
240.000	.000244	1.000000	.963E+04
260.000	.000143	1.000000	.565E+04
280.000	.000085	1.000000	.336E+04
300.000	.000051	1.000000	.202E+04
320.000	.000031	1.000000	.122E+04
340.000	.000019	1.000000	.747E+03
360.000	.000012	1.000000	.458E+03
380.000	.71E-05	1.000000	.282E+03
400.000	.44E-05	1.000000	.174E+03
420.000	.27E-05	1.000000	.107E+03
440.000	.17E-05	1.000000	.662E+02
460.000	.10E-05	1.000000	.408E+02
480.000	.64E-06	1.000000	.251E+02
500.000	.39E-06	1.000000	.154E+02
520.000	.24E-06	.999920	.943E+01
540.000	.15E-06	.996816	.575E+01
560.000	.88E-07	.969453	.349E+01
580.000	.53E-07	.878302	.211E+01
600.000	.32E-07	.717722	.126E+01
620.000	.19E-07	.530104	.755E+00
640.000	.11E-07	.361222	.448E+00
660.000	.67E-08	.232232	.264E+00
680.000	.39E-08	.143383	.155E+00
700.000	.23E-08	.086066	.900E-01
720.000	.13E-08	.050624	.520E-01
740.000	.75E-09	.029323	.298E-01
760.000	.43E-09	.016775	.169E-01
780.000	.24E-09	.009493	.954E-02
800.000	.14E-09	.005320	.533E-02

**** Fitted distributions of load cycle amplitude ****

Vertical bending moment

Weibull distribution
P(exceed) = exp(-(x/k)**beta)
Weibull k (MNm) :   20.8062
Weibull beta   :   .8536
Mean   :   22.5766 (MNm)
Std deviation   :   26.5549 (MNm)

Gumbel distribution
P(exceed) = 1 - exp(-(exp(-alpha(x - u))
Gumbel u (MNm) : -53.0322
Gumbel alpha (/MNm) :   .0267
Mean   : -31.4332 (MNm)
Std deviation   :   47.9934 (MNm)

Load	P(Exceed)		
(MNm)	Observed	Weibull	Gumbel
20.00	.425933	.380288	.132411
40.00	.186885	.174281	.079861
60.00	.083012	.084618	.047601
80.00	.038180	.042552	.028175
100.00	.018266	.021939	.016607
120.00	.009067	.011532	.009765
140.00	.004652	.006156	.005734
160.00	.002460	.003330	.003364
180.00	.001336	.001821	.001973
200.00	.000743	.001006	.001156
220.00	.000422	.000560	.000678
240.00	.000244	.000315	.000397
260.00	.000143	.000178	.000233
280.00	.000085	.000101	.000136
300.00	.000051	.000058	.000080
320.00	.000031	.000033	.000047
340.00	.000019	.000019	.000027
360.00	.000012	.000011	.000016
380.00	.71E-05	.65E-05	.94E-05
400.00	.44E-05	.38E-05	.55E-05
420.00	.27E-05	.23E-05	.32E-05
440.00	.17E-05	.13E-05	.19E-05
460.00	.10E-05	.79E-06	.11E-05
480.00	.64E-06	.47E-06	.65E-06
500.00	.39E-06	.28E-06	.38E-06
520.00	.24E-06	.17E-06	.22E-06
540.00	.15E-06	.10E-06	.13E-06
560.00	.88E-07	.60E-07	.77E-07
580.00	.53E-07	.36E-07	.45E-07
600.00	.32E-07	.22E-07	.26E-07

620.00	.19E-07	.13E-07	.15E-07
640.00	.11E-07	.81E-08	.91E-08
660.00	.67E-08	.49E-08	.53E-08
680.00	.39E-08	.30E-08	.31E-08
700.00	.23E-08	.18E-08	.18E-08
720.00	.13E-08	.11E-08	.11E-08
740.00	.75E-09	.70E-09	.63E-09
760.00	.43E-09	.43E-09	.37E-09
780.00	.24E-09	.26E-09	.21E-09
800.00	.14E-09	.16E-09	.13E-09

**** Fitted distributions of maximum lifetime load cycle amplitude ****

Vertical bending moment

Weibull distribution
P(exceed) = exp(-(x/k)**beta)
Weibull k (MNm) : 660.3448
Weibull beta : 11.3893
Mean : 631.5430 (MNm)
Std deviation : 67.1749 (MNm)

Gumbel distribution
P(exceed) = 1 - exp(-(exp(-alpha(x - u)))
Gumbel u (MNm) : 609.7956
Gumbel alpha (/MNm) : .0272
Mean : 631.0432 (MNm)
Std deviation : 47.2125 (MNm)

Load	P(Exceed)		
(MNm)	Observed	Weibull	Gumbel
20.00	1.000000	1.000000	1.000000
40.00	1.000000	1.000000	1.000000
60.00	1.000000	1.000000	1.000000
80.00	1.000000	1.000000	1.000000
100.00	1.000000	1.000000	1.000000
120.00	1.000000	1.000000	1.000000
140.00	1.000000	1.000000	1.000000
160.00	1.000000	1.000000	1.000000
180.00	1.000000	1.000000	1.000000
200.00	1.000000	.999999	1.000000
220.00	1.000000	.999996	1.000000
240.00	1.000000	.999990	1.000000
260.00	1.000000	.999975	1.000000
280.00	1.000000	.999943	1.000000
300.00	1.000000	.999875	1.000000
320.00	1.000000	.999739	1.000000
340.00	1.000000	.999479	1.000000
360.00	1.000000	.999002	1.000000
380.00	1.000000	.998154	1.000000
400.00	1.000000	.996691	1.000000
420.00	1.000000	.994239	1.000000
440.00	1.000000	.990234	1.000000
460.00	1.000000	.983849	1.000000
480.00	1.000000	.973907	1.000000
500.00	1.000000	.958784	1.000000
520.00	.999920	.936327	.999990
540.00	.996816	.903824	.998718
560.00	.969453	.858119	.979099
580.00	.878302	.795973	.894240
600.00	.717722	.714819	.728792

620.00	.530104	.614023	.531349
640.00	.361222	.496495	.356095
660.00	.232232	.370068	.225611
680.00	.143383	.247432	.138004
700.00	.086066	.143282	.082640
720.00	.050624	.068705	.048865
740.00	.029323	.025767	.028679
760.00	.016775	.007033	.016759
780.00	.009493	.001276	.009769
800.00	.005320	.000138	.005685

**** Conditional Probabilities for Loads Exceeding Threshold ****

Conditional probabilities are for cycle loads exceeding threshold level
Vertical bending moment
Threshold level : 600.000 (MNm)
Cycle exceedence probability : .320199E-07

Condition probabilities for ship speed

Ship speed (knots)	P(speed)
10.0	.1463
18.0	.8537

	1.0000

Condition probabilities for ship heading

Ship heading (deg)	P(heading)
.0	.0062
30.0	.0041
60.0	.0012
90.0	.0000
120.0	.0001
150.0	.3565
180.0	.6318

	1.0000

Condition probabilities for significant wave height

Wave height (m)	P(Hs)
.5	.0000
1.5	.0000
2.5	.0000
3.5	.0000
4.5	.0000
5.5	.0000
6.5	.0000
7.5	.0000
8.5	.0002
9.5	.0021
10.5	.0130
11.5	.0451
12.5	.1057
13.5	.1994
14.5	.6345

	1.0000

Condition probabilities for zero-crossing wave period

Wave period (s)	P(Tz)
3.5	.0000
4.5	.0000
5.5	.0000
6.5	.0478
7.5	.3808
8.5	.4257
9.5	.1314
10.5	.0138
11.5	.0005
12.5	.0000
13.5	.0000

	1.0000

Conditional probabilities for wave height and period combinations
Cell values are number of occurences per million
Blank cells indicate zero probability

	Wave Period Tz (s)										
Hs (m)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
.5											
1.5											
2.5											
3.5											
4.5											
5.5											
6.5											
7.5					2						
8.5				23	107	21					
9.5			3	278	1384	449	18				
10.5			20	1449	7609	3610	283	4			
11.5				4159	23680	15251	1944	58			
12.5				6938	49332	41304	7767	398	6		
13.5				15142	78323	83150	21109	1646	41		
14.5				19770	220393	281906	100229	11699	483	7	

Sum of conditional probabilities : 1.000000

References

[1] A.E. Mansour, P.H. Wirsching, M.D. Lucket, A.M. Plumpton, and Y.H. Lin, "Structural Safety of Ships," *Transactions, Society of Naval Architects and Marine Engineers* **105** (1997).

[2] J.P. Sikora, A. Dinsenbacher, and J.E. Beach, "A Method for Estimating Lifetime Loads and Fatigue Lives for Swath and Conventional Monohull Ships," *Naval Engineers Journal* **95**(3), 63–85 (1983).

[3] C. Guedes Soares and T.E. Schellin, "Long Term Distribution on Non-Linear Wave Induced Vertical Bending Moments on a Containership," *Marine Structures* **124**(3-4), 333–352 (1996).

[4] J. J. Jensen and M. Dogliani, "Wave-induced Ship Hull Vibrations in Stochastic Seaways," *Marine Structures* **124**(3-4), 353–387 (1996).

[5] K.A. McTaggart, "SHIPMO7: An Updated Strip Theory Program for Predicting Ship Motions and Sea Loads in Waves," DREA Technical Memorandum 96/243, March 1997.

[6] D.L. Chow and K.A. McTaggart, "Validation of SHIPMO7 and PRECAL Predictions with a Warship Model," DREA Technical Memorandum 97/203, November 1996.

[7] K.A. McTaggart and D.L. Chow, "Validation of SHIPMO7 and PRECAL Predictions with the CPF Hydroelastic Model," DREA Technical Memorandum 97/216, August 1997.

[8] British Maritime Technology Limited, *Global Wave Statistics*, Unwin Brothers, London, 1986.

[9] J.R. Paulling, "Strength of Ships," in *Principles of Naval Architecture* (Society of Naval Architects and Marine Engineers, 1989), Vol. 1, Ch. 4.

[10] P. Thoft-Christensen and M. J. Baker, *Structural Reliability and Its Applications*, Springer-Verlag, 1982.

[11] K. McTaggart, I. Datta, A. Stirling, S. Gibson, and I. Glen, "Motions and Loads of a Hydroelastic Frigate Model in Severe Seas," *Transactions, Society of Naval Architects and Marine Engineers* **105** (1997).

[12] Y.S. Shin, J.S. Chung, W.M. Lin, S. Zhang, and A. Engle, "Dynamic Loadings for Structural Analysis of Fine Form Container Ship Based on a Non-linear Large Amplitude Motions and Loads Method," *Transactions, Society of Naval Architects and Marine Engineers* **105** (1997).

[13] P.D. Sclavounos, D.C. Kring, Y. Huang, D.A. Mantzaris, S. Kim, and Y. Kim, "A Computational Method as an Advanced Tool of Ship Hydrodynamic Design," *Transactions, Society of Naval Architects and Marine Engineers* **105** (1997).

[14] Canadian Climate Centre, "Wind/Wave Hindcast Extremes for the East Coast of Canada, Volume 1," Technical Report, Prepared under contract by MacLaren Plansearch Ltd. and Oceanweather Inc., 1991.

[15] K.A. McTaggart, "Capsize Risk Prediction Including Wind Effects," in *Proceedings of the Third Canadian Marine Hydrodynamics and Structures Conference* (Dartmouth, Nova Scotia, August 1995), pp. 115–124.

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence Research Establishment Atlantic P.O. Box 1012, Dartmouth, N.S. B2Y 3Z7	2. SECURITY CLASSIFICATION (Overall security of the document including special warning terms if applicable.) UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.)

Prediction of Extreme and Fatigue Sea Loads Using Linear Theory

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

McTAGGART, Kevin A.

5. DATE OF PUBLICATION (Month and year of publication of document.) June 1998	6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.) 54	6b. NO. OF REFS. (Total cited in document.) 15

6. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Technical Memorandum

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the reseach and development. include the address.)

Defence Research Establishment Atlantic
P.O. Box 1012, Dartmouth, N.S. B2Y 3Z7

9a PROJECT OR GRANT NUMBER (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 1.g.b	9b. CONTRACT NUMBER (If appropriate, the applicable number under which the document was written.)
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is ider.tified by the originating activity. This number mrst be unique to this document.) DREA Technical Memorandum 98/215	10b. OTHER DOCUMENT NUMBERS (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors; further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors; further distribution only as approved
( ) Distribution limited to government departments and agencies; futher distribution only as approved
( ) Distribution limited to defence departments; further distribution only as approved
( ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic annoucement of this document. This will normally correspond to the Document Availability (11). However, where futher distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected.)

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

This report presents three different approaches for determining exceedence probabilities of ship sea loads using linear strip theory. The first two approaches use nominal maximum loads for hourly and variable duration seaways, while a third approach considers individual load cycle amplitudes in all seaways. Of the three approaches, the load cycle approach appears to be most useful and can be used for both fatigue and ultimate load computations. Sample computations for the Canadian Patrol Frigate demonstrate the application of the methods. Gumbel distributions provide good fits to computed lifetime load exceedence probabilities. For load cycle and nominal hourly maximum loads, Weibull distributions provide superior fits. Future work should include three-dimensional hydrodynamic forces, nonlinear load effects, and the influence of wave conditions on ship speed and heading.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title).

bending moment
extreme values
fatigue
reliability
sea loads
shear
torsion
ultimate strength